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ADAPTING SUSTAINABLE FOREST MANAGEMENT TO CLIMATE CHANGE:

A COMPREHENSIVE REPORT ON SCENARIOS FOR VULNERABILITY ASSESSMENT

D. T. Price and K. J. Isaac

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Northern Forestry Centre

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D. T. Price[1] and K. J. Isaac[2]

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ABSTRACT

Changes in global climate expected during the 21st century will have profound impacts on forests in Canada and elsewhere. Sustainable forest management objectives will therefore require modification as part of the general need for adaptation to climate change. Work carried out for the Canadian Council of Forest Ministers has focused on developing and implementing tools and methods for adapting forest management in an uncertain future. While the uncertainties are considerable, these cannot be considered an excuse for delaying action, particularly in a long-term endeavor such as forestry. The report reviews scenarios and scenario analysis as one important approach to accounting for uncertainty in forest management decision making. Scenarios include the projections of future global economic and demographic growth as drivers of climate change, of future climate, and of the potential impacts of changes in climate on natural and managed ecosystems. In turn, local impacts on Canada's forests can have important consequences for dependent communities and regional economies, which can feed back to global scenarios. The report discusses the availability of scenario data, the processes involved in developing local scenarios by stakeholders, and the application of scenarios as part of a vulnerability assessment process for sustainable forest management systems. Case studies of scenarios used in regional and national assessments of climate change impacts on forests are reviewed. Sources of information on scenarios are provided in three appendixes.

RÉSUMÉ

Les changements du climat mondial prévus au cours du XXI^{e} siècle auront de profondes répercussions sur les forêts au Canada et à l'étranger. Il faudra modifier les objectifs de gestion durable des forêts en raison du besoin généralisé de s'adapter aux changements climatiques. Les travaux réalisés pour le Conseil canadien des ministres des forêts ont mis l'accent sur l'élaboration et la mise en œuvre d'outils et de méthodes permettant d'adapter la gestion forestière en fonction d'un avenir incertain. Si les incertitudes sont considérables, elles ne peuvent cependant pas être invoquées comme excuse pour retarder la prise de mesures, en particulier dans un projet à long terme comme la foresterie. Ce rapport passe en revue des scénarios et en fait l'analyse, une importante approche permettant de tenir compte des incertitudes lors de la prise de décisions en matière de gestion forestière. Les scénarios comprennent les projections à l'égard de la croissance économique et démographique dans le monde comme facteurs des changements climatiques, du climat futur et des répercussions possibles des changements climatiques sur les écosystèmes naturels et les écosystèmes gérés. À leur tour, les répercussions localisées sur les forêts canadiennes peuvent entraîner des conséquences importantes pour les collectivités tributaires des forêts et les économies régionales, ce qui peut ensuite alimenter les scénarios mondiaux. Le rapport traite de la disponibilité des données de scénarios, des processus que suivent les intervenants pour développer des scénarios locaux ainsi que de l'application de scénarios dans le cadre d'un processus d'évaluation de la vulnérabilité en lien avec les systèmes de gestion durable des forêts. Les auteurs se penchent aussi sur des études de cas de scénarios utilisés aux fins d'évaluations régionales et nationales des répercussions des changements climatiques sur les forêts. Les sources d'information sur les scénarios étudiés sont fournies dans les trois annexes.

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As Canada's forest sector continues to transform in order to thrive in a globalized world, its members are recognizing the need to adapt proactively to climate change. The purpose of adaptation is to minimize the potential negative impacts, while capitalizing on possible opportunities that an altered climate may bring. A major thrust occurred in 2008 after the Council of the Federation meeting when the Canadian Council of Forest Ministers (CCFM) established the Climate Change Task Force (CCTF) to enable provinces, territories, and the federal government to work together on climate change related issues. The CCFM, with direction from the premiers, asked its CCTF to begin working collaboratively on climate change adaptation. The CCTF's first step was to establish a Technical Analysis Group (TAG) comprising subject matter experts whose mandate was to develop tools and strategies to facilitate the incorporation of climate change into all aspects of sustainable forest management (SFM) in Canada.

This report originated from ideas and discussions within the TAG who identified the need for a comprehensive understanding of the value of scenarios in decision making, as carried out by forest managers and policy makers working to achieve and maintain SFM in Canada. Initially, this work was conceived as a review of climate scenarios and their importance in informing managers, analysts, and researchers about the range of uncertainty in future climate and its impacts on managed forests. Gradually, the focus broadened into a wider view of scenarios: more than projections of future climate, scenarios for use in SFM must also consider how societal factors, both local and global, may interact with climate change and with its impacts on forests and forestry.

As the breadth of the work increased, the need for a comprehensive document to complement a shorter CCFM report entitled *Adapting sustainable forest management to climate change: scenarios for vulnerability assessment* (see www. ccfm.org) gradually emerged. This technical report is, therefore, an in-depth, state-of-the-art review of the approaches used in developing and applying climate change scenarios in SFM policy, planning, and practice in Canada.

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EXECUTIVE SUMMARY

Introduction

Sustainable forest management (SFM) seeks to “maintain and enhance the long-term health of forest ecosystems for the benefit of all living things while providing environmental, economic, social, and cultural opportunities for present and future generations” (CCFM 2008). However, the world is now being subjected to significant changes in climate that pose a serious threat to both Canadian forests and the attainment of SFM objectives. Further climatic changes are all but inevitable in coming decades, regardless of efforts to mitigate global emissions of greenhouse gases (GHGs), although the precise consequences for Canada’s forests and for SFM remain highly uncertain.

A major concern of researchers and managers is that present-day forests and forest management will need to be adapted to a changing climate, if the supply of forest goods and services is to remain sustainable (Lemprière et al. 2008; Johnston et al. 2010a, 2010b; Williamson et al. 2010). Adapting SFM to account for climate change is likely to be essential if the sustainability objective is to be achieved and maintained “for present and future generations”. Significant challenges remain, however, in identifying appropriate adaptations and deciding where and when they should be implemented. Uncertainty in the timing, location, and magnitude of climate change and its impacts will need to be considered in planning SFM for the future. For example, increased occurrence of fires, insect outbreaks, and mortality related to drought are all expected (e.g., Trenberth et al. 2003), but the need for, and cost of, adaptation measures to address these threats will vary across the country and according to future management objectives.

Scenarios are tools that can be used to account for uncertainty in decision making in a systematic, ordered way. (For example, they can be used to assess sensitivity of the system of interest to plausible levels of change.) Scenarios can be viewed as thought experiments that allow exploration of how future climate may differ from that of the present, leading to alternative impacts on a system of interest, such as a managed forest. Scenarios are therefore often the products of some form of “model”, meaning any representation of ideas about how climate changes may affect the system of interest (i.e., models can be conceptual, qualitative, or quantitative).

Scenario analysis allows decision makers to consider a range of possible futures and to develop adaptive measures that are more likely to remain effective within that range of possibilities. The effects of multiple uncertainties, including the potential consequences of adaptations, can be explored, enabling the development of strategies and decisions that are more robust in most of the potential outcomes. It is important that scenario analysis be guided by stakeholders with competing long-term visions of what is desired for the future (not all of which may be achievable), to direct the implementation of both short- and long-term adaptation measures (Bizikova et al. 2009). SFM practitioners will also need to be aware of the wider consequences of any planned adaptation and be ready to modify actions if and when necessary (Gray 2012).

Scenarios analysis is an appropriate means of integrating considerations of climate change into long-term planning for SFM. The use of scenarios of future climate and of its impacts, particularly at the local scale (i.e., an area corresponding to a forest management unit or a community and the land base that supports it), is also a key element of assessing the vulnerability of SFM to climate change. Vulnerability assessment has become an established approach to understanding and responding to the potential effects of climate change on a system of interest (e.g., IPCC 2001; Metzger et al. 2005; Smit and Wandel 2006), such as a managed forest (Williamson et al. 2012).

The purpose of this report is to review the topic of scenarios, to identify those that are relevant to SFM, and to examine how they can be used to envision future climate conditions and the responses of socioecological systems, as these systems affect SFM. Supporting information on the availability of scenarios developed for Canada, and other resources, are documented in the appendices. The report also provides guidance on how scenarios can be used in vulnerability assessments and in the development of adaptation strategies for SFM.

Causes of Uncertainty

Future climate change and its effects on the environment and human society are uncertain for several reasons. Uncertainty can be classified as reducible or irreducible. First, there is largely irreducible uncertainty about how human activities will unfold in the future. Population growth, economic development, land use changes, and other human activities all emit GHGs into the atmosphere and lead to anthropogenic climate change. Although much effort and resources are being invested in mitigation, GHG emissions continue to increase; hence, some level of climate change is inevitable, owing to past and ongoing contributions to the atmospheric GHG burden.

Second, the earth's climate system is complex, and the scientific knowledge of how it will respond to increases in atmospheric GHG concentrations is incomplete. This is considered to be reducible uncertainty: earth system scientists (including physicists, climatologists, and ocean scientists) aim to improve their understanding of the underlying processes and hence gradually increase the ability to predict how the system will respond to different levels of GHG emissions. Much of what is known about the global climate system is captured in the global climate models (also known as general circulation models, for which the abbreviation GCM is equally applicable). Although much has been learned about global climate responses to changes in GHG forcing using GCMs in recent decades, these complex numerical models remain simplistic in their representation of reality, and uncertainty will remain in their projections for years to come. There is, nevertheless, consistency in the general future trends they project, as well as strong consensus within the mainstream scientific community that these trends are correct and consistent with recent observations (e.g., IPCC 2013). As research tools, the GCMs differ in the details of how they simulate the many interacting climate processes. Consequently, projections created by different GCMs often differ, for example, in the regional and temporal distributions of changes in precipitation. It is important to recognize that modern GCMs have been tested extensively by comparing simulations with observed climate trends at both global and regional scales, and have proved able to capture many of the large-scale meteorological processes and observed historical trends in climate.

Third, there is reducible uncertainty about the interacting responses of ecosystems (including Canada's forests) to significant shifts in the distributions of "climate zones" and to changes in climate variability and extremes. While research continues to explore these responses, present capacity to predict when and where they will occur, for all the important species in all forest ecosystems found across Canada, is rather limited (e.g., see Johnston 2010a). Additionally, terrestrial ecosystems, oceans, and the cryosphere (icecaps and glaciers) all contain vast natural reservoirs of GHGs (or of materials that may release them). Each of these systems may respond to climatic change in ways that alter the storage of GHGs and potentially increase their release to the atmosphere, causing positive feedbacks that can drive further changes in global climate. The quantification of feedback effects remains an area of ongoing research.

Fourth, human adaptation will become increasingly important as the climate changes, but how and when adaptation will occur is another significant source of climate change uncertainty. Some of this uncertainty is likely reducible, because as climate change unfolds, some adaptation strategies (e.g., water conservation) will become inevitable. On the other hand, future human behavior, influenced to a greater or lesser extent by laws, ethics, and financial factors, remains largely unpredictable. Societal adaptation to the impacts of climate change could also cause feedback effects on the climate system as people adapt their behavior in anticipation of climate change or in response to its impacts. For example, increased demand for air conditioning could amplify electric power consumption and increase the release of GHGs from coal-fired power stations. Alternatively, humans might create additional green space in cities and urban areas as a means of addressing rising temperatures (providing shade and surface cooling through evapotranspiration). Such an adaptive measure could also have a negative feedback effect by sequestering carbon in urban forests.

A further aspect of uncertainty is that many attempts to understand the future are based on an implicit assumption that events will unfold as a relatively continuous and gradual process. Many scientists recognize that there is always the potential for surprises to occur, including extreme climatic events and natural disasters such as earthquakes. These events are generally considered to be of low and uncertain probability with largely unquantifiable consequences and are therefore difficult to fit into future planning based on projections of known and measurable trends. However, the unprecedented flooding that ravaged southern Alberta, including central Calgary, in June 2013 was a clear demonstration of how "low-probability extreme events" can be surprisingly damaging and costly; it is likely that climate change was a contributing factor. Further, nonlinear responses of perturbed systems (such as degrading permafrost driven by climate warming) may seem unlikely, but they have a huge "downside risk" with largely irreversible, long-term global impacts.

What are Scenarios and How are They Useful?

Scenarios are plausible stories about the future. They have been used widely since the 1960s to provide decision makers with a systematic approach to analyzing long-term implications of investment alternatives and other strategic decisions (Moss et al. 2010). Scenarios shift the focus away from predicting the future and instead provide alternative views of what may happen, to allow the potential consequences of a range of plausible outcomes to be assessed and compared. Unlike predictions, which aim to state what is most likely to happen in the future, scenarios are single instances (or projections) of many possible futures that might occur. For example, a modern weather forecaster may use results from several atmospheric models, combined with his/her own experience and intuition, to predict the most likely weather over the next 6–24 hours or longer. If the model results were treated as scenarios, however, then the forecaster would make no such determination. Scenario analysis then considers a range of scenarios, all of which are treated as equally likely to occur in reality.

Scenarios provide a means of assessing the consequences of uncertain outcomes, including the potential consequences of low-probability, high-impact events. Awareness of climate change should include understanding that considerable uncertainty remains in predicting what exactly will change in the future. Even as knowledge increases, future uncertainty will remain; consequently, adaptation to climate change impacts should not be delayed in the hope that uncertainty will be reduced (Opitz-Stapleton 2010). Hence, scenarios are an essential tool for exploring the extent of uncertainty and its implications for decision making. Making uncertainty explicit in the decision-making process can help users identify adaptation measures that are both flexible and appropriate for a range of possible futures.

Storylines and the Scenario-axis Approach

A storyline is a narrative description of a scenario (or a family of scenarios) that highlights the main characteristics and dynamics, as well as the relationships, among key driving forces (Nakićenović et al. 2000). These relationships are often described using the "scenario-axis" or "matrix" approach, which involves framing storylines around two contrasting axes to represent important drivers of change for which there is considerable future uncertainty. The four quadrants created by the intersection of the axes represent "scenario families" that allow a spectrum of possible futures to be visualized, but each quadrant is often represented by a single "marker scenario" (Rounsevell and Metzger 2010). This allows for the exploration of uncertainty with a degree of analytical rigor and makes the process of scenario development more transparent to participants, facilitating comparisons among different scenarios and their underlying assumptions (Berkhout et al. 2002; Rounsevell and Metzger 2010). The process is highly subjective, so it is important to acknowledge and document the potential for bias in the storylines, due to political ideologies, personal beliefs, or worldviews (Metzger et al. 2010).

Global assessments of climate change have, for example, often begun with an evaluation of historical social and economic development trends that have had an important influence on GHG emissions. Storylines describing possible future socioeconomic trends are used to illustrate how GHG emissions could change and how this could affect the global climate. The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) is a textbook example of using the scenario-axis approach and scenario storylines in conjunction with quantitative modeling (Nakićenović et al. 2000). The SRES scenarios are based on a matrix with a horizontal axis that captures political development ranging from "regional connectivity" to "global cooperation and policy", and a vertical axis that contrasts "economic and social development founded on free market principles" with "development based on environment and social equity". The four resulting quadrants then lead to distinct storylines that produce markedly different projections of GHG emissions, now commonly known as A1, A2, B1, and B2.

Developing Scenarios

While many methods can be used to develop scenarios, the general process is relatively consistent and applicable at a range of spatial scales. Metzger et al. (2010) identified five steps, namely (1) state goals and define the temporal and spatial boundaries for the scenarios; (2) determine the most crucial and uncertain drivers of change; (3) describe the framework in which the scenarios will be developed and state important assumptions; (4) develop the storylines and describe the possible alternative futures to which they lead; and (5) interpret these alternative futures to create scenarios.

Several methods are used to interpret the possible consequences of climate change, such as quantitative models, empirical analogs, expert judgment, and participatory processes, although a combination of these methods may be used to develop scenarios in different contexts. Quantitative models, including GCMs, biophysical models, and econometric models, use numerical scenario data to simulate potential changes in the system of interest. Temporal analogs are observed phenomena or experiences that provide insight into how similar situations or conditions could be dealt with in the future. For example, local stakeholders might review how a community responded to a recent large wildfire and consider how local preparedness could be adapted in anticipation that such events would become more frequent and (or) more severe. Spatial analogs use observations of phenomena or experiences occurring in one location to identify possible future implications for other locations (generally at higher latitude or elevation). Expert input is often provided by scientists and subject specialists who possess knowledge about critical drivers of change, can address important information gaps, or have experience addressing similar types of issues. Participatory processes refer to the involvement of local players (i.e., stakeholders) and others in scenario development and discussions of how climate change could affect local conditions. Invited specialists may play a key role as providers of information or as facilitators of the discussion, but local participants frequently play a central role in determining what questions scenarios should address, clarifying information provided by others, and deciding how this information will be used in adaptation strategies.

Obtaining Information for Local Scenarios

The scenarios used in any assessment should be appropriate for the time period, location, and scale of interest. There are two distinct approaches to building local scenarios. The top-down approach (Dessai and Hulme 2004) generally involves some form of downscaling of information from global scenarios (or other large-scale data sources) to the local region of interest (such as a forest management unit). Downscaling techniques are applicable to statistical projections of future demographic and economic trends, as well as to projections of climate change and its biophysical and socioeconomic impacts. The downscaling approach chosen will vary according to the type of large-scale data available, with some methods being highly numerical and others more qualitative. Regardless of the technique, the objective is to transform information available at coarse spatial resolution so that it can be applied at the local scale in a meaningful way.

The complementary bottom-up process accounts for local conditions, obtained from local sources of information and data. Some form of analysis is generally required to determine which attributes are important and how much they are likely to be affected by climate change. The bottom-up approach typically reflects the cultural, economic, and political viewpoints of the stakeholders developing the scenarios. In general, it will require identification of the purpose of the analysis and hence of the key factors the local scenarios should consider. This could be done using the scenario-axis method mentioned previously to define local storylines, which are then used to outline the alternative possible futures.

Scenarios of Climate Change

Although most climate change scenarios are now derived from GCM simulations, useful information about potential responses of communities and ecosystems can be obtained using simpler approaches. A good example is to add 1, 2, and 3 °C increments to observed mean temperatures coupled with increases and decreases in precipitation of 0%, 5%, or 10%. It may also be sufficient to assume that seasonal and inter-annual variability will not change dramatically during the period of the scenario. A problem remains though, because these simple approaches to projecting changes in key climatic variables may create unrealistic combinations of changed conditions.

Hence, one key advantage of using climate change projections produced by GCMs is that they should be internally consistent, meaning that correlated changes in projected climate variables result from basic physical relationships captured in the GCM. Internal consistency also means that possible shifts in the relationships of these variables over simulated time are derived physically rather than being guessed at or ignored. However, GCM projections will generally require downscaling to create useable scenarios of future climate at regional or local scales and often need some consideration of local climatic conditions. Downscaling techniques include spatial interpolation of the coarse-resolution GCM output; dynamical downscaling, as characterized by regional climate models (RCM); or local-scale statistical downscaling.

Although they differ in the detailed spatial distribution and timing of projected changes, notably in precipitation patterns, the results from different GCMs forced by the same GHG emissions scenario are in general agreement. For Canada, GCMs are consistent in projecting that the greatest warming will occur in the far north (increases of 5–10 °C for annual mean daily minimum temperature by 2100), and the least on the east and west coasts at the southern border with the United States (3–5 °C increase in annual mean daily minimum temperature by 2100). Canada wide, the mean increases in temperature are approximately double the projected global increases. Price et al. (2011) have concluded that increases of at least 2 °C in mean annual temperature are virtually inevitable for most of Canada's forested regions by 2050, compared with ca. 2000.

Rising temperatures will also allow atmospheric humidity to increase, leading to increases in mean precipitation of about 1%–2% per 1 °C of warming (Hengeveld 2006; Trenberth et al. 2003), although local change can vary from decreases to much larger increases. Price et al. (2011) found that several GCMs were consistent in projecting increases in mean annual precipitation for most of Canada, with the largest proportional increases in the far north. However, these mean increases will not be sufficient to offset the overall increase in potential evapotranspiration resulting from the warmer conditions; hence, increased frequencies and intensities of drought events are to be expected. Many of the increased risks due to climate change result from changes in the frequency and intensity of extreme events (e.g., occurrence of large wildfires and severe floods) that can trigger widespread changes in ecosystems and costly damage to human settlements. Kharin et al. (2007) have interpreted GCM projections of changes in extreme events, finding that climate warming generally produces greater extremes in both temperature and precipitation, but with considerable spatial variation around the mean global trend.

Considering the local impacts of climate change in the context of broader global socioeconomic trends may also be important. This adds to the complexity of scenario analysis, but can reveal situations where future trends (e.g., in global timber markets) will require adaptation strategies completely different from those required for climate change alone. Changes in forest management may then be required to reduce adverse effects, or take advantage of any opportunities, that appear plausible.

Biophysical Scenarios

Empirical methods for assessing potential impacts of climate change on local forests are often based on interpretations of local observations. These include the anecdotal observations of life-long residents in remote regions; formal monitoring programs such as networks of permanent sample plots to track volume growth and stand development; intensive short-term field experiments designed to enhance understanding and provide key information for improving process models; and volunteer science programs coordinated by professional researchers, such as the PlantWatch project. Learning from recent or historical events (using the past as an analog for the future) or from events in other regions (using space as an analog for time), as well as seeking input from specialists and stakeholders, are also practical means of developing adaptations to present-day management practices.

Ecological models are of value for predicting the potential impacts of changes in climate on forests, but it is important that some aspect of their functioning is sensitive to changes in the climate or weather data used to drive them. This limits the choice to some extent and favors process-based models over traditional statistical models, such as the growth and yield models traditionally derived from historical permanent sample plot data. Of course not all models produce credible results, and not all forestry practitioners engaged in SFM have access to (or take advantage of) the expertise or resources needed to use models successfully. Further, some forestry practitioners may discount models as a useful source of information for decision making.

Results from many models forced by a range of projections of future climate indicate a general northward shift of the climate zones that presently support particular tree species and forest ecosystems in Canada. However, many species, and trees in particular, will be unable to colonize new regions as fast as the zones of optimal climate are expected to move (even under moderate scenarios of future climate). For species and genotypes that are not already widespread over a large latitudinal range, these shifts in climate conditions will cause many species to become "maladapted", leading to increased vulnerability to stressors, reduced productivity and competitive ability, and generally reduced ability to survive. On the other hand, the generally warmer conditions expected to occur in Canada could support a greater diversity of species, particularly those presently restricted to ranges in the eastern United States. Climate change will also affect the occurrence of natural disturbances, including wildfires and pest outbreaks, as well as accelerating the degradation and loss of permafrost in the northern boreal zone.

Scenarios of ecosystem responses can be key inputs to vulnerability assessments for SFM because they provide alternative plausible views on how the environment of a given location (forest management unit, region, or nation) might change. Further, climate change may mean that the social and economic benefits of SFM (employment, wealth, recreation, etc.) will also change — leading to further socioeconomic impacts that should be considered in SFM vulnerability assessments.

Social and Economic Scenarios

Socioeconomic scenarios (SESs) are generally used in two ways: (1) to illustrate the possible trajectories of socioeconomic drivers of change and (2) to describe future socioeconomic impacts of climate change. In the first case, SESs explore the possible ways in which socioeconomic factors, such as demographics and culture, economics, natural resource use, and governance and policy, could evolve in the future. Given a large and increasing global population, changes in these factors are almost certain to affect anthropogenic GHG emissions and stimulate land use conversions. Hence these factors are considered socioeconomic drivers of changes in climate and other environmental attributes.

SESs are often based on common assumptions about relationships between development and environmental outcomes (van

Drunen and Berkhout 2009). While they often differ in the ascribed sensitivity of environmental change to different socioeconomic drivers, they generally reflect gradual development that is influenced by one of a strong policy push for sustainability, social fragmentation, environmental collapse, or institutional failure or by the emergence of new human values and forms of development (Raskin et al. 2005). Many SESs also reflect common assumptions about relationships among different drivers of global environmental change. For instance, many scenarios are characterized by trade-offs between economic growth and environmental and social sustainability, although these changes are not necessarily mutually exclusive (i.e., it may be possible for both to occur at the same time) (Rounsevell and Metzger 2010).

The new process for assessing impacts of global socioeconomic development is termed Representative Concentration Pathways (RCP). This approach was is being supported by the IPCC for the Fifth Assessment and aims to capture the linkages among global socioeconomic development, GHG emissions, and global climate responses in a more integrated way than has occurred for previous assessments (Moss et al. 2010). The RCP approach should also facilitate better feedbacks between local-scale responses (including climate change adaptation and mitigation) and the projection of global trends.

The second way in which SESs are used in impact and vulnerability assessments is to evaluate the socioeconomic impacts of climate change. These effects can be assessed using a number of different methods, although an important distinction exists between market and nonmarket impacts. Where ecosystems are associated with economic activities, socioeconomic impacts can be estimated using monetary or market values. Changes in forest sector economic well-being (sector competitiveness, international trade of forest products, employment income, government tax revenues, etc.), for example, can be modeled to reflect changes in timber supply using measures such as allowable annual cut (AAC) or maximum sustainable yield (Hauer et al. 2001).

The impacts of climate change on nonmarket forest values including changes in the supply of nontimber forest products (food, fuel, and medicines) and on recreational services and tourism (visits to national parks or participation in skiing, fishing, or hunting) can also be evaluated, though data for some goods and services can be limited. To date, very few studies have quantified nonmarket social and economic costs of climate change impacts on forest ecosystem services. Instead, impacts are often discussed qualitatively, if at all (NRTEE 2011). Evolving methods such as economic valuation techniques and alternative approaches such as landscape values mapping (systematically linking qualitative information about values with spatial data) may be able to represent climate change impacts more successfully.

Many assessments appear to underestimate the socioeconomic impacts of climate change, and socioeconomic factors are often excluded from adaptive and mitigative decision making (Adger et al. 2009). Future societal changes can be projected assuming no effects of climate change and then added to different projections of future climate impacts to approximate the combined socioeconomic effects (Feenstra et al. 1998). However, some social consequences of the impacts may not be captured, and some human activities (e.g., mitigation) can produce climate change feedbacks. The economic costs of different adaptation actions (including no action) can be assessed using conventional discounting methods to compare the costs and benefits of alternative actions at different times in the future. However, there is no consensus on appropriate discount rates that both reflect the interests of present-day society and acknowledge the needs of future generations.

Vulnerability of Sustainable Forest Management to Climate Change

Creating scenarios for use at the scale of a forest management unit (say, 1000 to 10 000 km^2) will typically depend on localized scenarios of climate change, which are often derived from GCM simulations, though other methods exist. Interpreting the impacts of these different climate change scenarios generally requires some form of model. The model could be a computer simulation or it could equally be the results of a discussion among specialists and local forest managers. In principle, all four methods of scenario development mentioned earlier are applicable to both ecological and socioeconomic impact analyses.

Scenarios play a key role when carrying out vulnerability assessments (Williamson et al. 2012). Climate change scenarios represent alternative levels of exposure to climate (as it varies over time or space). Impacts scenarios (i.e., scenarios of the impacts resulting from both future climate change and other social and economic drivers) combine information about the sensitivity of forest ecosystems, and that of dependent socioeconomic groups or sectors, with information about the projected local exposure to climate change.

Vulnerability (V) may be defined as

$$V = f(I, \mathrm{AC})$$

where the impacts, I, are some combination of exposure and sensitivity (e.g., the product), and adaptive capacity, AC, is inversely related to V. At present, there is little consensus on how these relationships should be captured mathematically, however, so these mathematical representations will not be discussed further (see also Williamson et al. 2012).

In Canada, the existing national system of criteria and indicators (C&I), developed to track progress in achieving and maintaining the sustainability of managed forests, may be a logical basis for monitoring and projecting the impacts of climate change on SFM. Although not designed specifically to do so, work has begun to explore how well existing indicators capture the effects of climate change and their usefulness in measuring SFM under a changing climate, either as the indicators stand or following some modification of the definition and (or) methods of measurement (Steenberg et al. 2013). Effects of changes in exposure on the selected indicators could be explored and used to estimate the sensitivity of the SFM system (as the observed or simulated change in one or more indicators, relative to the amount of climate change, either experienced or projected). It could be important, though, to account for the effects of preexisting stressors, which may exacerbate sensitivity to climate.

Vulnerability assessment differs from more conventional impact assessment by accounting for the role of human adaptive capacity, which implies some capability of mitigating the negative effects of climate change, and taking advantage of any beneficial effects (Williamson et al. 2012). As described in Williamson and Isaac (2013), adaptive capacity is partly determined by assets that can be used for adaptation, such as human expertise, natural resources, finances, infrastructure, and institutions, as well as the ability to use these resources when needed. Williamson and Isaac (2013) suggest that describing the assets available for adapting SFM to climate change, and exploring experiences with past climate events, are two ways to understand and assess adaptive capacity. They also present several other options for describing, analyzing, and managing adaptive capacity in the context of SFM. Vulnerability can then be analyzed by comparing adaptive capacity to the potential impacts of climate variability and extremes as well as to long-term changes in mean climate. Assessments might also explore how adaptive capacity could change as a consequence of various socioeconomic development pathways (captured in SES), for example, in response to changes in the regional economy or greater accessibility to higher education.

Once vulnerabilities are determined, adaptation options can be identified that reduce the exposure or sensitivity of SFM to climate change and (or) that increase adaptive capacity over time — both processes that reduce vulnerability. Next, the costs and benefits of each adaptation option can be calculated and compared across scenarios. The objective is to identify "no-regret" measures (which are beneficial even in the absence of climate change), "low-regret" measures (where the cost of adaptation is low relative to the impacts that would be avoided), and "robust" measures (which produce net benefits across all scenarios regardless of cost). Additionally, there are potential trade-offs and synergies between adaptation and mitigation options that may need to be considered, particularly at the intersection of energy alternatives, carbon sequestration, and natural resource management (IPCC 2013). Research continues to explore potential conflicts and complementarities, although many climate change strategies treat adaptation and mitigation separately.

Case Studies: Using Scenarios to Assess Impacts of Climate Change on Sustainable Forest Management

A review of four case studies for forest management systems across Canada shows that impact scenarios can be developed in many ways. The Forest Futures Project (FFP) (e.g., (Duinker 2008; Frittaion et al. 2011) and the National Round Table on the Environment and the Economy (NRTEE 2011) "climate prosperity" study were both national in scope but differed in that FFP was strongly participatory, whereas NRTEE adopted a quantitative economic analysis. In FFP, 13 distinct drivers of change affecting the Canadian forest sector were identified; two of these were selected as particularly important but uncertain (environmental change and the societal value placed on forests) and therefore used as contrasting axes to develop scenarios. In the NRTEE study, the scenario axes captured mean annual growth in Canadian gross domestic product (GDP), ranging from low (1.3%) to high (3%), and the IPCC SRES A2 and B1 GHG emissions scenarios though several GCM projections were used to assess impacts of future climate on wood supply.

The other two case studies were focused more locally. The first was a sensitivity analysis of key drivers affecting future AAC carried out by Millar Western Forest Products Ltd. for its Defined Forest Area in central Alberta (Yamasaki et al. 2008). Process modeling of climate change impacts on future forest productivity and occurrence of fires was combined with projections of future population growth and developments in the oil and gas sector (which were contributing to significant losses in the operable land base), for a total of nine different scenarios. The second local study was an impact assessment carried out by Natural Resources Canada for the community of Vanderhoof in central British Columbia (Williamson et al. 2007). Vanderhoof's primary economic sector is in forestry and wood products, but this sector is now severely threatened by widespread mortality of lodgepole pine forests due to mountain pine beetle. The Vanderhoof analysis was a hybrid, featuring multiple climate scenarios used to model impacts on forest composition and productivity and future changes in AAC and the occurrence of fires, combined with a participatory process to capture local knowledge from community residents and stakeholders. A scenario-axis approach was also used to assess four potential futures based on two levels of climate change ("moderate" or "significant") and strong or weak socioeconomic development.

Conclusions

As part of a climate change vulnerability assessment for SFM, scenarios are a valuable, possibly essential, tool for investigating the consequences of uncertainty and for developing adaptation strategies that will be robust over a range of possible future outcomes. Recently, there has been increasing recognition that wider uncertainties, in global societal and economic trends as well as in global climate, need to be addressed in a more integrated manner. Climate change scenarios are only part of the story, and more effort needs to be focused on integrating other global trends, including land use changes and other effects of population growth, new technologies, and economic shocks. The implications of these global trends can be considered locally, but the issues are complex and not easily quantified, suggesting that specialist input in local-scale analysis is also needed. Of the various approaches available for developing comprehensive local scenarios, a participatory process that involves both the local stakeholders (who provide the local context) and experts (who can interpret the global drivers) should be of particular benefit to SFM because it requires the active engagement of both groups.

The effects of adaptations to SFM, whether they prove successful or not, are often not considered in scenario analyses. That is, when adaptation strategies are implemented on a large scale, there is the potential for further climatic feedbacks at local and even larger scales that may need to be taken into account. As knowledge of the consequences of different adaptation options increases, it will become necessary to factor some of these into scenario development.

Several researchers have suggested that qualitative analysis and participatory approaches can be used more widely in impacts analysis (Naess et al. 2006; Berkhout and van Drunen

2007; Cohen and Waddell 2009; Rounsevell and Metzger 2010). Scientists and other specialists will remain as valuable sources of information and can contribute to the development of local storylines and scenarios. However, when local stakeholders are actively involved, the discussion forces them to think about the possibilities, promotes ownership, and leads to more relevant, place-based scenarios. In fact, the origin of the scenarios used to frame the discussions about adaptation may prove to be less important than the discussion itself. Discussion can reveal the possibility space for the future and lead to more robust decision making.

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INTRODUCTION

"…climate prediction should not be the central tool to guide adaptation to climate change…."
(Adger et al. 2009)

Recently observed trends around the world, namely those of generally increasing temperature and other changes in weather patterns, are indicative of human-caused changes in global climate (i.e., global warming). Numerous analyses and model projections strongly suggest that even larger changes are almost inevitable in coming decades.

Climate change will have significant impacts on both forest ecosystems and on the technical and social dimensions of sustainable forest management (SFM). Within Canada, SFM has been defined by the Canadian Council of Forest Ministers (CCFM 2008) as:

> Management that maintains and enhances the long-term health of forest ecosystems for the benefit of all living things while providing environmental, economic, social and cultural opportunities for present and future generations.

The problems in achieving SFM can be both natural and human in origin. Climate change (among other global environmental changes) represents a major threat to Canada's SFM objectives, with pervasive effects on many aspects of forests, including site productivity, species distribution and abundance, and the frequency and intensity of natural disturbances (Lemprière et al. 2008; Johnston et al. 2010a, 2010b; Price et al. 2013; Williamson et al. 2010). Changes in climate are also likely to affect the vast array of social, economic, and cultural benefits obtained from forests, as well as causing direct effects on human well-being. In particular, climate influences the types and levels of risks, notably those of extreme events, and hence can greatly affect the quality of life experienced by a local population. Some recent examples of catastrophic events affecting human well-being in rural Canada that can be linked to climatic extremes include:

- an unprecedented ice storm affecting eastern Ontario, southern Quebec, and parts of New Brunswick and Nova Scotia in 1998
- major wildfires affecting the communities of Kelowna, British Columbia, in 2003 and Slave Lake, Alberta, in 2011
- an unprecedented outbreak of mountain pine beetle affecting some 15 million ha (1 ha = 2.471 acres) of forests in British Columbia alone
- unprecedented seasonal flooding events in Manitoba and Quebec in 2011
- unprecedented summer rainstorms causing disastrous flooding in Alberta in 2013

The magnitudes and consequences of climate change in Canada are uncertain, but it is clear that they will be widespread. Many of the impacts on forests and forestry will be damaging, though some may be relatively easy to manage, while others may even be beneficial. Forestry practitioners, managers, policymakers, and community leaders therefore stand to benefit from learning about the impacts of climate change on forests, the forest industry, and the human populations they support (spiritually and culturally, as well as economically). Further, they will need to develop new strategies and management practices to mitigate and adapt to these impacts, and to capitalize on any opportunities that emerge, while also achieving and maintaining sustainability. Important questions include:

- Can forests be managed sustainably in regions where limited moisture and (or) high summer temperatures may already limit tree productivity and survival?
- How must SFM policies and practices be altered in regions where changes in climate will likely favor different tree genotypes from those that are present today?

- How can the effects of increased natural disturbances be integrated into SFM planning?
- How will the forest industry need to adapt to ensure continued viability?
- How will Canadian society, and forest-based communities in particular, be affected by, and adapt to, these impacts and the changes needed to maintain SFM?

With such questions in mind, the CCFM is leading the development of a suite of vulnerability assessment tools to assist forest management practitioners and community leaders with the integration of climate change into SFM. These include a framework approach for the SFM vulnerability assessment outlined by Williamson et al. (2012) and guidelines for implementation of this approach by Edwards et al. (2015).

Vulnerability assessments typically begin by examining how the system of interest (such as a forest or human community) is influenced by current climate and climate variability (e.g., Smith et al. 2001; Ford et al. 2006; Smit and Wandel 2006). The critical next step is to determine how future climate conditions could differ from those of the present, and what these changes mean for forests and for SFM. It then becomes possible to use this information to identify adaptation options and strategies and then integrate them into management planning.

This report provides in-depth information on the use of scenarios to envision future climate conditions and the responses of socioecological systems, as these affect SFM in Canada. Specific objectives of the report are to

- explain what scenarios are, where they come from, and why they are useful
- review the types of scenarios that are applicable to the topic of vulnerability assessment for SFM
- distinguish global scenarios (e.g., of climate change) from local scenarios (which may combine climate change, other factors, and their impacts on forests and SFM)
- provide information on accessing scenarios available "off-the-shelf"
- discuss techniques available for developing local scenarios for forest systems and dependent communities or sectors
- discuss how scenarios can be used when carrying out SFM vulnerability assessments and developing adaptation strategies
- review studies of climate change impacts on forest systems across Canada where scenarios have been used

Relevance of Scenarios to Sustainable Forest Management

An important objective of a vulnerability assessment for SFM is to understand the range of possible climate change impacts on managed forests, as well as on the human communities that depend on the forest for goods and services, such as recreation and employment. The assessment process (e.g., as described by Williamson et al. 2012) should help those responsible for SFM to determine the exposure and sensitivity of the forest resource to climate change, and to account for adaptive capacity in the human systems that both care for and are dependent upon forest resources. Vulnerability assessment may then lead to development of new strategies and practices to be implemented in adaptive forest management (see Gray 2012). In this context, scenarios allow the range of possible climate change and its consequences to be explored, with the objective of developing more robust and flexible adaptive management plans.

The term "SFM systems" refers to both the forest ecosystem and the social and economic activities involved in managing and deriving benefits from forests. In principle, an assessment of climate change impacts on an SFM system can be done at many different scales, ranging from an individual forest management unit up to the national or even global scale (Fig. 1). Scenarios can be used to envision the potential impacts of climate change and other factors on multiple aspects of an SFM system, including the maintenance of biodiversity, water resources, and carbon sequestration, as well as other economic, social, and cultural benefits (e.g., maintaining employment, a strong forest sector, and the health and safety of forest-based communities). In this report, these are referred to as "SFM scenarios". Approaches for developing SFM scenarios are presented, taking into account both global-scale factors (which include climate change, and global demographics and economic events) and concerns at the local scale (such as safety, employment, and recreational value). The objective is to provide a generally applicable approach that can suit the interest or focus for any particular vulnerability assessment.

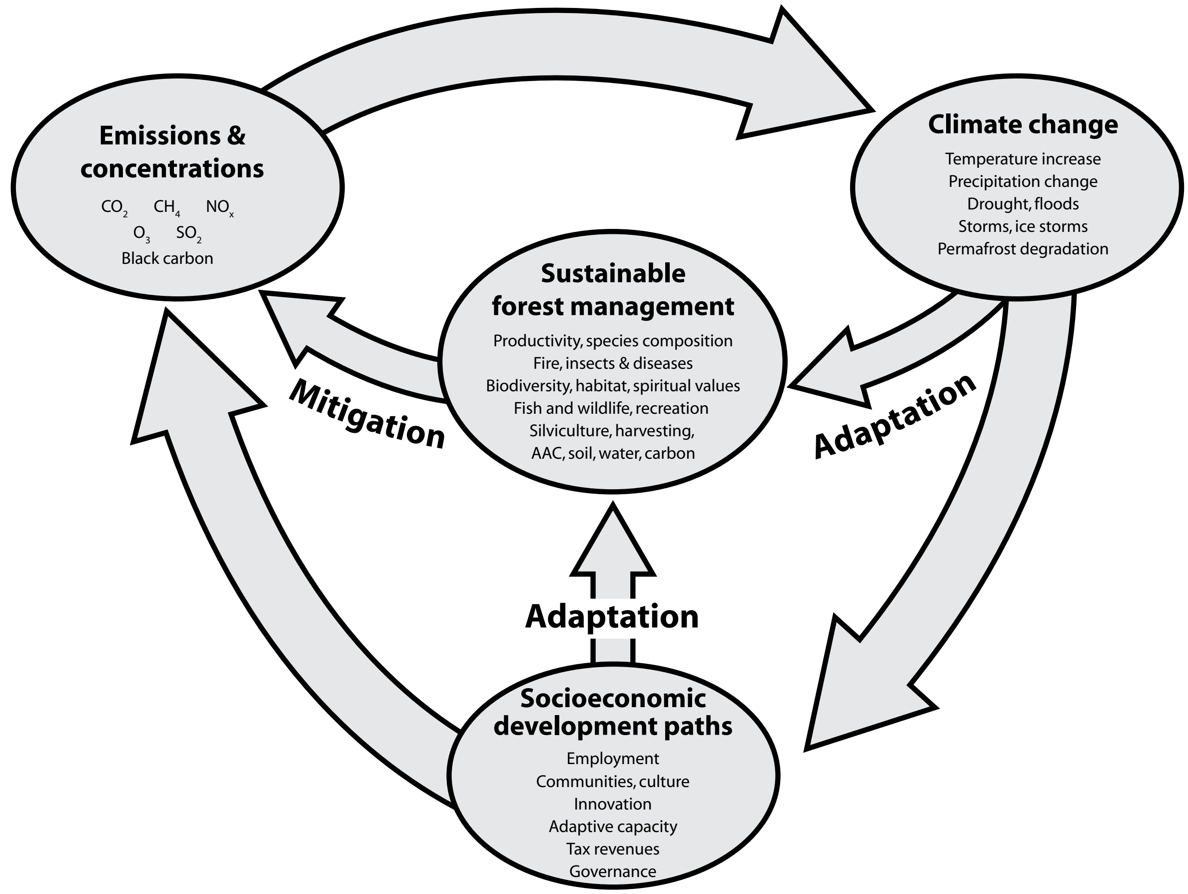

Figure 1. The linkages between climate change and sustainable forest management, including both mitigation and adaptation. Arrows show the cycle of cause and effect, and indicate the societal pressures to adapt forest management in response to climate change. Forest management is one of very few human activities where successful adaptation to climate change can also contribute to mitigation. In addition to the direct impacts of climate on social and economic well-being of human communities, there are also important socioeconomic benefits of Canada's forests that will be affected by climate change. It is the intersection of climate change impacts and socioeconomic drivers for forest management where scenarios for SFM need to be focused. Adapted from IPCC (2001b).

THE UNCERTAINTY PROBLEM: WHY SCENARIOS ARE NEEDED

A major challenge in adapting to climate change is that there is uncertainty about how much the climate will change, and how fast, as well as how these changes will affect forest ecosystems and the social and ecological benefits that forests provide. Scenarios are an important tool that can be used to assess this uncertainty and its consequences for adaptation decisions. The purpose of this section is to review why the future is uncertain and hence why scenarios are useful.

Uncertainty is a key issue in understanding global climate change and adapting to its effects. Although a great deal is known about how climate has changed in the recent past, much remains to be learned about how the global climate system functions, and hence great uncertainty will remain in projections of future climate (e.g., see Trenberth 2010). It is important to understand that some level of climate change is virtually certain, even though the details may remain fuzzy for many decades. This fuzziness, or the hope that it will disappear, should not be seen as a reason for delaying adaptation. Even as knowledge increases, there will always be uncertainty about the future; therefore, adaptation should not be delayed in the hope that uncertainty will be reduced (Opitz-Stapleton 2010). The purpose of scenario planning is to understand the effects of uncertainties (including the possible consequences of inaction), and to facilitate the making of difficult decisions. In the context of SFM, scenarios can illustrate the effects of a future where climate conditions are different from those of the present or past, but in uncertain ways, leading to a consideration of what these uncertain changes will mean for the forest resource, its management, and the benefits it brings to society. By exploring the extent of uncertainty, its causes, and its implications for decision making through scenario analysis, and by making these issues explicit in the adaptation process, flexible and appropriate responses can be developed.

Causes of Uncertainty

The global climate system is complex and dynamic, and although much has been learned about how the system operates and how human activities may alter it, predicting how it may behave in the future remains a huge challenge. The underlying theory of a causal relationship between human activities and global climate change is clear. However, the many interacting climate processes and human actions (including adaptation and mitigation) add considerable uncertainty to what will happen in reality. Present-day global social and economic activities are not only key drivers of environmental change, but many of these activities are also sensitive to it. Scenarios of future human development, its effects on global climate, and further consequences of these changes on human and natural systems can therefore provide alternative plausible views on how the social, economic, and natural environment of a location (the community, region, or country) might change and affect activities such as SFM (Fig. 1). Better understanding of the range of these possibilities can therefore help forest managers at all levels to develop more resilient adaptation strategies.

Uncertainty can be classified as either reducible or irreducible. In the context of climate change, reducible uncertainties include the scientific understanding of the primary causes of radiative warming of the atmosphere and the many feedback effects that may mitigate or exacerbate this primary effect. The irreducible uncertainties about climate change include our ability to forecast whether humans will be able to regulate greenhouse gas (GHG) emissions and over what time frame.

Climate Change Uncertainty

Much of what we know about the causes and potential effects of global warming is derived from general circulation models (GCMs). The GCM projections of future global climate trends are based on scenarios of future global demographic and economic factors, as captured in global integrated assessments. These factors drive both fossil fuel consumption and changes in land use, such as deforestation, and inevitably lead to the release of GHGs to the global atmosphere (Fig. 1). Conversely, humans may take action to reduce GHG emissions and could therefore play a critical role in reducing the global warming trend. These human activities, therefore, contribute to changes in global atmospheric concentrations of GHGs and, while largely unpredictable, must be key inputs to GCM projections of future climate. The lack of predictability of human actions over the next hundred years or more is a major cause of today's irreducible uncertainty about climate change.

A second cause of uncertainty about future climate resides in the current state of scientific knowledge about the global climate system, much of which is represented in the GCMs. Although they are necessarily complex, all climate models remain gross simplifications of reality, requiring many internal approximations that limit their accuracy and the confidence placed in their predictions. Moreover, as new understanding develops, these internal approximations can differ substantially among models and even between different versions of the same model. In particular, global climate is affected both directly by changes in atmospheric composition and indirectly by the many feedbacks, both physical and biological, that the initial climatic changes may cause — in terrestrial ecosystems, oceans, and the cryosphere (icecaps and glaciers). Some atmospheric responses to warming, such as increased water vapor content, leading to more cloud formation and increased rain and snowfall, will also cause feedbacks on climate, some of which may mitigate the warming trend. Not all of these feedback processes are represented in current-generation GCMs.

Hence, simulations by different GCMs (with the same GHG forcing) will likely differ in the spatial distribution as well as rate and magnitude of the projected changes, and in the correlation of these changes among different climate variables. These differences can be interpreted as scientific uncertainty in how the climate is likely to respond to the specified GHG forcing. It is important to recognize, however, that in spite of these limitations, the GCMs are able to show that nearly all warming observed since ca. 1850 can be explained by GHG concentration increases. This accounts for the effects of variations in solar output (due to sunspot activity and Earth's orbital eccentricities) and major volcanic eruptions (which contribute to increased aerosol concentrations, increasing planetary reflectance and hence reducing solar heating occasionally), as well as other anthropogenic factors such as pollutants and stratospheric ozone depletion (Randall et al. 2007).

The established GCMs have been consistent for more than a decade in predicting global-scale warming trends and that past GHG emissions will continue to affect future climate, possibly for centuries, owing to the thermal lag effect of the oceans (e.g., Meehl et al. 2005; Wigley 2005; Pierce et al. 2011). Recent observations of a 15-year "hiatus" in the warming trend since 1995 (e.g., Fyfe et al. 2013) are no cause for complacency — variations of this magnitude have occurred repeatedly since 1850, and the decade 2001–2010 was still the warmest, globally, on record. See also papers by Kosaka and Xie (2013) and Cowtan and Way (2014) on possible causes contributing to the "hiatus".

In essence, significant warming is virtually inevitable in the next few decades, regardless of what human actions may occur. Moreover, the GCMs are consistent in projecting greater future warming with stronger GHG forcings. Disagreement remains among the GCMs in the detailed geographic and seasonal distributions of projected temperature increases and the changes in other climatic variables, notably precipitation. Taking all of these uncertainties into account, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has projected mean increases in globally averaged surface air temperature by the period 2081–2100, ranging from as small as 0.3 °C to as much as 4.8 °C, compared with the mean for the period 1986–2005 (IPCC 2013). Increases at the lower end of this range (0.3–1.7°C) are obtained with the very optimistic Representative Concentration Pathways (RCP) 2.6 GHG scenario, which can be achieved only with rapid major reductions in global GHG emissions. The largest increases (2.6–4.8°C) result from the most pessimistic RCP 8.5 scenario. Temperature increases at the center of this range are unprecedented in at least the last 200 000 years of Earth's paleohistory. Given that the IPCC AR5 projections do not account for some important feedbacks, and that recent anthropogenic GHG emissions have been increasing at a rate comparable to the worst-case scenarios (Le Quéré et al. 2009; IPCC 2014), it seems likely that actual warming will be at the higher end of the projected range, unless global action is both swift and effective.

There is much ongoing debate about whether uncertainty of future climate change has been reduced, as the GCMs have become more complex and presumably more accurate (e.g., Reichler and Kim 2008; Trenberth 2010; McKenney et al. 2011). The general story is that the range of projected warming has not been appreciably reduced in two or three generations of GCMs, but this is partly due to an increasing number of GCMs, contributing to a greater range of projections, even though the more established models have tended to converge. Also, there is little doubt that new information about some atmospheric feedbacks and the attempts to include them in newer GCMs, such as the radiative effects of low clouds in future conditions (Clement et al. 2009), leads to new uncertainty, which offsets any convergence among the GCMs (Trenberth 2010). Some GCM simulations performed for the IPCC Fifth Assessment also considered the effects of biospheric feedbacks on global climate, such as increased forest fires (e.g., Arora et al. 2011). A few of these feedbacks (such as possible increases in photosynthesis due to higher CO_2 concentrations, known as CO_2 fertilization) may mitigate the GHG release, but others will certainly accelerate it, further increasing uncertainty in the magnitude and timing of climate change. Mote et al. (2011) point out that the full range of unknowns cannot be captured by the range of uncertainty implied by multiple GCMs, even though this is often implicitly assumed to be the case. In principle, model uncertainty is reducible, but at least in the context of climate change, it may be some time before improvements to GCMs result in a demonstrable reduction in the uncertainty attached to climate projections.

Uncertainty about the Impacts of Climate Change

Figure 2 indicates how uncertainty about climate change and its effects are an accumulation of multiple uncertainties, including

- human activities causing environmental changes in coming decades
- physical responses of the global

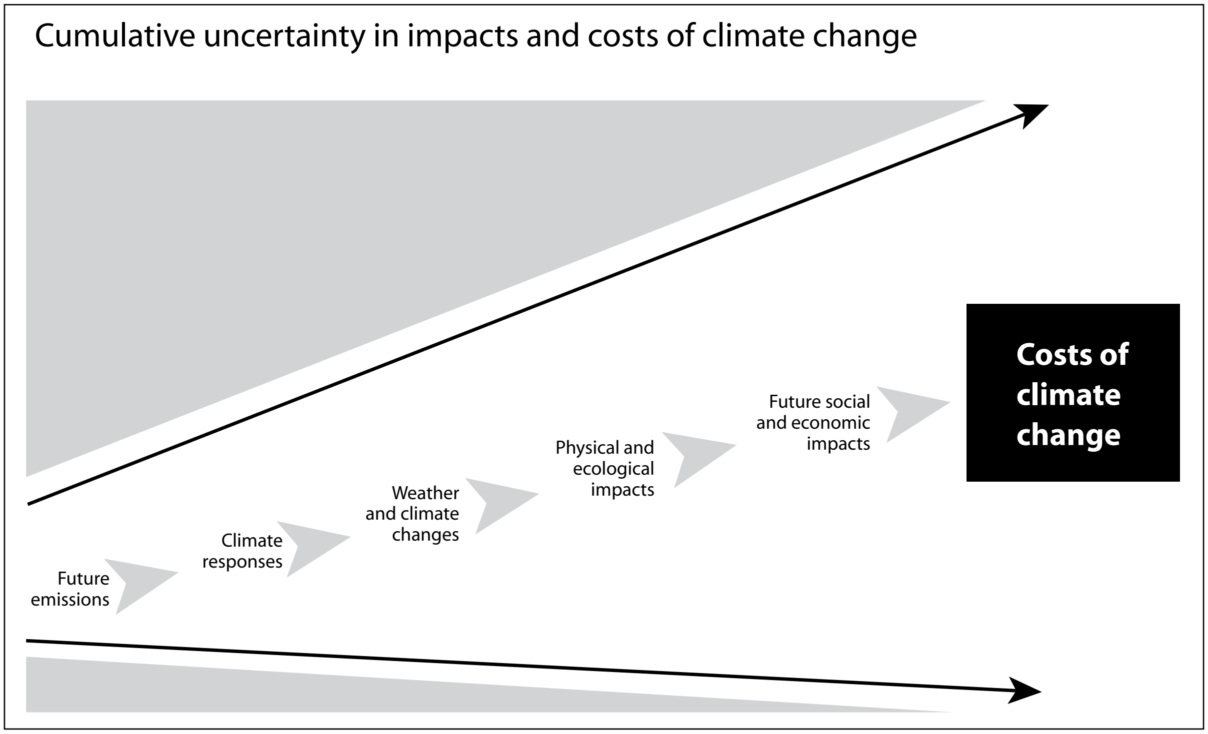

Figure 2. The cumulative nature of uncertainty about the consequences (costs) of climate change resulting from multiple and interdependent causes. Adapted from NRTEE (2011); originally from Menne and Ebi (2006).

climate system to both natural and anthropogenic perturbations, including possible surprise events

- biospheric responses to global change (both terrestrial and aquatic), which may be gradual (and sometimes beneficial) or rapid (in which case they are generally damaging)
- effects on human activities in response to environmental changes (both climatic and ecological), which include mitigation and adaptation efforts

All of these elements can be captured in some form of model. Every model, whether it is highly numerical or conceptual, contains numerous simplifications of reality and broad assumptions that are rarely completely correct. Unfortunately, much of our knowledge about climate change and its potential impacts necessarily stems from assessments that link multiple model projections (climate models → ecological models → economic models) (e.g., Irland et al. 2001). This suggests that the associated uncertainties propagate (perhaps multiplicatively) at each stage of integration. Additionally, the further into the future that these impacts are projected, the greater the range of uncertainty, both for the magnitude of the impacts and their potential costs.

Climate Surprises: Extreme Events and Tipping Points

In climate science, the phrase "extreme event" generally refers to the occurrence of phenomena that are relatively unusual for a particular region or location, but which can be characterized by measurable criteria that can be compared with previous events. Examples include both short-lived weather events such as storms (characterized by intensity and duration of precipitation, maximum wind speed, and the amount of damage) and longer term climatic events such as severe droughts (measured by the number of years of occurrence and the economic and social costs of crop failures, such as insurance payouts, farm bankruptcies, and farmer suicides).

A series of major Atlantic hurricanes in 2004–2005, and a general trend of increasing storm damage over the 1990s and into the 21st century, tend to confirm an anticipated trend of increasing storm intensity, as the heat retained in the atmospheric engine has gradually increased (Frich et al. 2002; Milly et al. 2002). The IPCC's AR5 indicates that although there is generally little evidence of increased storm frequency occurring since 1950, it is "virtually certain" that there has been increased storm activity in the North Atlantic since 1970 (IPCC 2013). This report also concludes it is likely that there have been more increases than decreases in the occurrence of heavy precipitation events over land. GCMs may provide a basis for projecting how the frequency and occurrence of such events may alter in the future (e.g., Kharin and Zwiers 2005; Kharin et al. 2007), though this is far from a mature science. However, some recent research casts doubts on whether observed "extreme events" really exceed the range of natural variability, suggesting that they may not (yet) be a recognizable consequence of climatic change (Bouwer 2011).

There is also the potential for "tipping points" to be exceeded. Tipping points are shifts from one quasi-stable system state to another, such as a persistent change in ocean circulation patterns or an ecological transition, say from forest to grassland (e.g., Hogg 1997; Lenton et al. 2008), or even a change in the global climate system itself (e.g., Shuman 2012). Socioeconomic systems also have tipping points that when crossed can have significant and unpredictable outcomes. A recent example is the banking crisis of 2008, where obscure lending policies allowed individuals and corporations to borrow money that they could not afford to pay back (Simkovic 2009). Loan defaults, plummeting real estate prices, and reduced investor confidence contributed to the collapse of many large financial institutions, followed by major government bailouts and severe unemployment.

The transition from one state to another may occur gradually or abruptly, in response to progressive changes in some controlling condition. In ecosystems, transitions may result from a gradual but persistent change in climate, leading to a new state with reduced functioning compared with the ecosystem it replaced (e.g., in terms of annual primary productivity or species diversity). Such transitions therefore compromise the services provided by the ecosystem. One relevant example is the potential for climate warming to cause permanent losses of permafrost in northern boreal spruce-dominated woodland ecosystems that support woodland caribou. The melting of permafrost causes waterlogging, eventually killing the tree cover and making the vegetation unsuitable as habitat. Replacement of the spruce by new forest trees can take 80–100 years (Quinton et al. 2009). Alternatively, transitions can result in an improved state, for example, where fossil fuels are replaced by low-carbon energy sources induced by a gradually rising price for carbon (Edenhofer et al. 2006). Reaching this type of tipping point in the socioeconomic system may actually help to prevent tipping points in the climate system (Lenton 2010).

What are Scenarios and How are They Useful?

Scenarios are logical, internally consistent, plausible alternative portrayals of the future (Nakićenović et al. 2000; Raskin et al. 2005; Carter et al. 2007). They have also been described as thought experiments that allow consideration of how the future may differ from the present, leading to a range of potential alternative consequences. Scenarios are used as heuristic planning tools by illustrating possible future conditions in which decisions will need to be made. For example, scenarios have been widely used in strategic planning for business, military operations, public policy development, and environmental assessments (Berkhout et al. 2002; Duinker and Grieg 2007; Moss et al. 2010; Rounsevell and Metzger 2010).

Most scenarios used in assessments of climate change vulnerability and adaptation are exploratory (i.e., they consider multiple possible future states based on variations in the main factors that affect a system) rather than normative (i.e., where a single desirable future is outlined or defined to identify the decisions needed to achieve such a future, a technique also known as "backcasting") (Berkhout et al. 2002). Exploratory scenarios may be based on the assumption that past trends will continue linearly into the future. For example, projections of global climate change are ultimately derived from scenarios of future global population growth and economic development. The latter scenarios could be based upon the extension of past trends — for example, estimating future population by extrapolating past population growth rates. However, this provides a very limited vision of what the future could bring. A more comprehensive approach is to envision multiple scenarios of the future that are based on novel types and rates of change. For example, concerns about climate change could lead to a shift in the values placed on forest ecosystems, resulting in increased conservation for carbon sequestration to mitigate GHG emissions. Another novel possibility is that increasing demand for energy and concerns about rising GHG concentrations from deforestation and the burning of fossil fuels could make the sustainable production of bioenergy increasingly profitable, with potentially serious implications for food production (Foley et al. 2011).

Scenarios are particularly valuable for exploring the effects of uncertainty, because comparing a variety of different scenarios shifts the analytical focus away from estimating the most likely path and towards determining the potential consequences of a range of different possible future situations and the most appropriate responses to each (Duinker and Grieg 2007). In this respect, it is important to emphasize the differences between scenarios and predictions and how these terms are both related to projections. In simple terms, a projection is a description of how the future may unfold under a given set of conditions. A climate projection, for example, generally refers to a single simulation performed with a climate model for a given scenario of future GHG emissions and other factors. A prediction or forecast is a statement that something is likely to happen in the future given certain conditions. Predictions are often based on some level of specialist knowledge, which might include computer model projections, that is considered more reliable than guesswork or complete ignorance.

In forecasting the weather, or how a forest fire may develop, for example, meteorologists may carry out many projections of what may occur, but the objective is to determine which of those projections is most likely to occur. Scenarios, on the other hand, should be regarded as "alternative images without ascribed likelihoods of occurrence" (Carter et al. 2007, p. 145). Multiple projections (which may be computer simulations or analyses by experts) can be treated as individual alternative scenarios, or they may be merged in some way to be represented as a single scenario. Scenarios may also be qualitative, generally meaning they are constructed by groups of stakeholders and specialists brainstorming the possibilities and developing coherent storylines — which may then be used to create plausible projections.

Scenarios allow decision makers to test their assumptions and broaden their perspectives of the future (Duinker and Grieg 2007). For activities such as forest management, the impacts of today's decisions may not manifest for several decades. With the expectation of significant but uncertain climate change, it becomes critically important to make decisions that are robust in a wide range of possible futures (Moss et al. 2010). This leads to the integration of future scenarios into the forest management planning process (i.e., scenario planning).

Exploring Tipping Points and Surprises Using Scenarios

To date, efforts to incorporate the occurrence of extreme climatic events, or the possibilities for tipping points to be exceeded, into scenario planning are relatively rare. Dessai and van der Sluijs (2007) argue that most thinking about future climate is based on an "evolutionary paradigm" (first proposed by Brooks (1986), who assumed that whatever happens in the future will occur as a "gradual and incremental unfolding of the world system in a manner that can be described by surprise-free models"). Events that are extremely rare (or even beyond human experience) tend to be ignored in scenarios of the future, even though if they were to happen, the consequences could be devastating (e.g., major earthquakes). Brooks (1986) suggests that this omission is driven largely by pragmatism, rather than by ignorance or reductionism, as practical methods to capture nonlinear and random events are generally lacking. Instead, the tendency is to assume that, over time, the effects of such events will be ironed out by the general trend (e.g., of climate warming) so that simpler models will capture most of the important consequences.

Although extremes and nonlinear events are not generally addressed in mainstream scenarios, some scenario studies specifically explore the impacts of major shocks or discontinuities in current trends, such as financial crises or environmental disasters (van Drunen and Berkhout 2009). For example, van Notten et al. (2005) review scenarios that address discontinuities and find that they often follow a common progression pattern: an abrupt discontinuous event occurs at the start of the scenario, leading to a series of other random events; an initial discontinuous event takes place and is followed by more gradual progress; or an abrupt discontinuity arises mid-scenario, and the description focuses on the causes, the incident, and the consequences.

Dessai and van der Sluijs (2007) recommend constructing an inventory of scenarios that consider discontinuous climate change or the consequences of extreme but rare events. A possible approach would be to assign a probability and potential consequences of a low-risk, high-cost scenario to investigate how extreme changes in global climate will play out. For example, the Canadian National Round Table on the Environment and the Economy (NRTEE) analysis of the potential costs of climate change to Canada considered four scenarios representing the combination of low and high rates of population growth and economic development. Each scenario followed the evolutionary paradigm, but was subjected to a probability distribution (Monte Carlo) approach with 10 000 independent simulations, using random adjustments to uncertain model assumptions. The extreme 5% and 1% of these results produced both very high and very low potential costs and might be used to gauge the impacts of high-cost outcomes of low-probability climate-change related events.

It is also possible to use scenarios to test whether the system of interest is resilient to surprises. Through brainstorming, scenario developers can build inventories of relevant causes of surprise events by scanning sources of historical information (both scientific and anecdotal). Resilience can be tested by applying the surprise scenario to the modeled system, assessing the impacts, and determining whether the system recovers from the impacts in a plausible way (Berkhout et al. 2002). The objective is to consider what would be a desirable course of action now if the surprise scenario were to occur in the future (Dessai and van der Sluijs 2007).

SCENARIO DEVELOPMENT AND APPLICATION

This section explores how scenarios are developed, including a discussion of how local scenarios suitable for use in sustainable forest management can be linked to larger scale scenarios obtainable from other sources.

Storylines and the Scenario-axis Approach

Scenarios are generally based on qualitative descriptions of the future (i.e., using words or images), with "storylines" being the most common form (Carter et al. 2007). A storyline has been defined as "a narrative description of system characteristics and dynamics and of the relationships among key driving forces" (Nakićenović et al. 2000). Storylines are often used as the basis of quantitative scenarios, although they may be a useful product in their own right (Carter et al. 2007).

A matrix, or scenario-axis approach, is frequently used to describe the relationships among two or more drivers of change in a qualitative yet structured way (Rounsevell and Metzger 2010). This involves framing the storylines around contrasting axes that capture the key social, political, or environmental drivers for which the rate and direction of change are thought to be particularly uncertain (Fig. 3). The four sectors (or quadrants) created by the intersection of the axes each define a range of possible future developments, often termed "scenario families", that reflect distinct futures associated with the directions of the key drivers. Scenario families are often illustrated as a group or by a single "marker scenario". This allows for the exploration of uncertainty with a degree of analytical rigor that makes the process of scenario development more transparent to participants and facilitates comparisons among different scenarios and their underlying assumptions (Berkhout et al. 2002; Rounsevell and Metzger 2010). It is important to recognize that this process is highly subjective, and the storylines that emerge may reflect certain political ideologies, personal beliefs, and worldviews. This may lead to a perception of bias in what is considered plausible or likely to unfold: some participants and others outside the scenario development process may not share the same views. Hence, Metzger et al. (2010) emphasize the importance of explicitly acknowledging and recording personal judgments and the implications of these for the resulting scenarios.

The matrix approach has been used to develop scenarios of future global socioeconomic development for many different types of analyses. In particular, it was used by the IPCC to "characterize the demographic, socioeconomic and technological driving forces underlying anthropogenic greenhouse gas emissions which cause climate change" (Carter et al. 2001). Figure 3 illustrates the matrix used by the IPCC in the Special Report on Emission Scenarios (SRES) to describe the most important yet most uncertain drivers of future GHG emissions (Nakićenović et al. 2000; also see Appendix 1).

Table 1 provides a short description of the storyline, driving forces, and GHG emissions associated with each of the four socioeconomic scenario families used in the IPCC SRES. A more detailed summary is provided in Table 3-9 of Carter et al. (2001). Additional information is also available in Appendix 1, including a link to quantitative descriptions of the SRES scenarios, their assumptions, and projections of associated future global climate.

Developing Scenarios

Metzger et al. (2010) describe scenario development as a five-step process. The first step involves the identification of goals for the scenario exercise and the definition of spatial and temporal system boundaries. In general, these include the wider context of the study, encompassing the ecosystems, economic sectors, geographic areas, and time horizons of interest (Carter et al. 1995). Challenges with setting these boundaries can often arise because of the uncertainty associated with longer time frames and limited availability of data at fine spatial resolutions. Next, the drivers affecting local conditions are identified, and the most crucial and uncertain ones are highlighted. Both

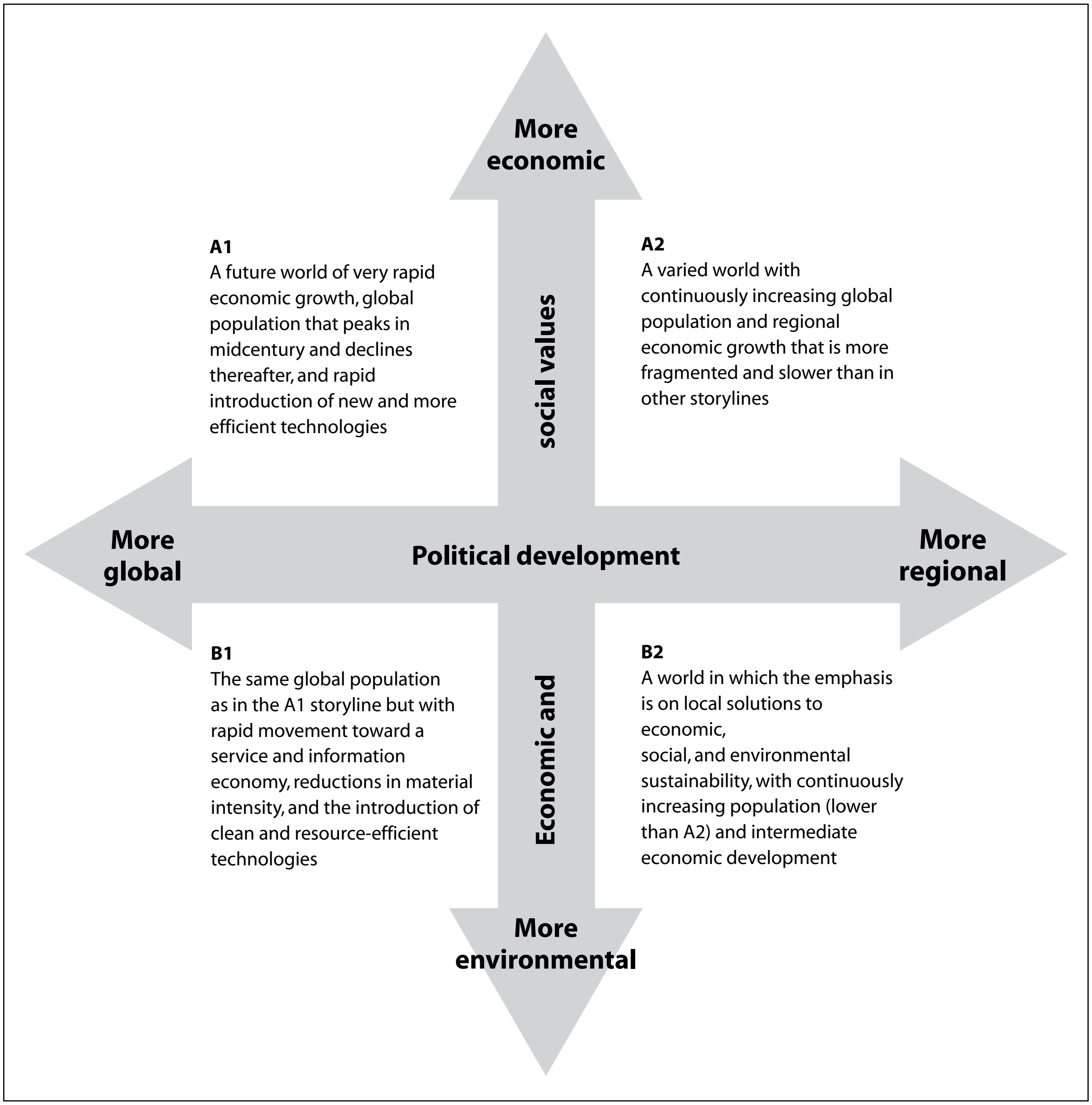

Figure 3. The scenario-axis approach using IPCC storylines (adapted from Nakićenović et al. 2000). The horizontal axis contrasts regional connectivity with global cooperation and policy, and the vertical axis contrasts development, emphasizing market liberalization with development that places growing value on the environment and equity.

climatic and nonclimatic drivers of change may be included, for example, population, economic growth, land use change, natural resource use, governance policy. The third step is to describe the framework around which the scenarios will be created and state the assumptions that will be used to project changes in the most important drivers. The matrix approach is a commonly used framework for scenario creation, though it is important to reiterate that the storylines that emerge are often highly subjective and may reflect the biases of those developing them (Metzger et al. 2010). In the fourth step, the qualitative storylines and trends in key drivers are used to describe alternative futures. Finally, the outcomes of the alternative futures are assessed using qualitative or quantitative methods.

The methods used to create scenarios of the impacts of climate change generally fall into one of four categories: quantitative models, empirical analogs, expert input, and participatory processes (see also Table 3–4 of Carter et al. (2001) for a comprehensive classification of the methods applied to different types of climate scenarios, with the advantages and disadvantages of each). Scenarios can be created using any of these methods or some combination. The selection of a particular method will normally depend on the resources available — including familiarity with the different approaches, and availability of suitable information and (or) expertise — as well as on the nature of the scenario being developed.

Table 1. The IPCC's scenario families as reported in Nakićenović et al. (2000)

	Scenarios			
	A1	A2	B1	B2
Storyline	Very rapid economic and population growth up to 2050. Decreases after peak in 2050s, with rapid implementation of energy-efficient technologies	Continuously increasing population, but slower economic growth that is regionally divided	Population growth similar to A1, but with economic restructuring away from material-intensive production towards clean technology and the provision of services and information	Local sustainability solutions with continuously increasing population and midrange economic development
Driving forces	Globalization and economic values	Regionalization and economic values	Globalization and environmental values	Regionalization and environmental values
GHG emissions[a] (Gt)	Medium–high (1499 Gt C)[b]	High (1862 Gt C)	Low (983 Gt C)	Medium–low (1164 Gt C)

[a] Total cumulative CO_2 equivalent in gigatonnes of carbon (C) by 2100.
[b] Marker scenario A1B.

Quantitative models use numerical data (such as the scenarios of future GHG concentrations) to simulate changes in the system of interest based on the best available knowledge. They include the GCMs, biophysical models, economic models, and engineering models. To be useful for climate change impacts assessment, a model must respond to changes in forcing climate variables, particularly temperature. Further, these responses should be tested, for example, by applying the model in multiple locations where good validation data are available.

Empirical analogs are qualitative assessments of observed phenomena treated as analogs of the future. They include a review of past extreme climatic events, such as droughts, heat waves, or severe storms, and a consideration of how the system of interest would respond, or need to be adapted, if such events became more frequent or more severe in the future. For example, local stakeholders might review how a community responded to a recent large wildfire and consider how local preparedness should be adapted. Hence, empirical analogs are particularly useful for assessing consequences of extreme events. Another example is investigating how present-day climate affects systems (ecosystems, agriculture, or other economic sectors, human communities, etc.) in other warmer/drier/wetter regions, treating these as analogs of the region of interest exposed to future climate. Ideally, any use of analogs will require that the systems being compared are similar in the details of their structure and organization (i.e., ecological, economic, or social, as applicable) (Ford et al. 2010).

Expert input is the use of informed judgment to identify and define drivers of socioeconomic, climatic, or environmental change or to fill in information gaps and "blend" model outputs into plausible scenarios (Abildtrup et al. 2006). Often, the experts are natural and social scientists who try to describe what is possible and plausible (Cohen and Waddell 2009) and whose advice should emphasize multiple possible futures and the uncertainty inherent in all future projections (Stirling 2010). When such experts disagree on the details, a range of interpretations can inform decision making on complex issues such as socioeconomic development and adaptation to the local impacts of climate change. Stirling (2010) also suggests that the reasons for different interpretations should be documented to highlight and identify the important value judgments that may need to be addressed in policy and decision making.

Participatory processes generally aim to broaden the knowledge contributing to storyline development by eliciting stakeholder input. An increasing number of impact and adaptation studies involve partnerships among scientific specialists and stakeholders to create local scenarios (Cohen and Waddell 2009). Stakeholder involvement can vary from providing basic information to very active participation (see section 2.3.2 of Carter et al. 2007). Stakeholders are often the local experts, with knowledge of past conditions and recent changes; the causes of recent changes (including impacts of climatic change); and insights into what may be of particular concern in the future. They will also be able to report on local impacts of extreme events, such as a severe drought or large wildfire. Cohen and Waddell (2009) emphasize that participatory dialogue is a two-way or multi-voice shared learning experience for all of the scientists, modelers, and stakeholders involved. It is not outreach or teaching, but instead focuses on incorporating climate change into current management and planning (i.e., mainstreaming).

Obtaining Information for Local Scenarios

Climate change will affect people and places differently across space and through time, so it is important that the scenarios used in any type of assessment are appropriate for the time period, location, and scale of interest. Scenarios of global climate change may be suitable for use in global analyses of ecosystem or socioeconomic impacts, but assessments focused at smaller scales (national, regional, local) will generally require that scenarios of possible future conditions be developed and interpreted at these scales.

Two broad approaches can be used to obtain information for smaller scale assessments of future conditions: top-down, which uses some form of downscaling of global scenarios to generate "nested local scenarios", and bottom-up, where local information about change is compiled from sources that are largely independent of global scenarios (see Fig. 4). A nested scenario is informed or constrained by larger scale (global or regional) scenarios; it may be a scenario of socioeconomic trends, climate change, environmental impacts, or some combination focused at a scale ranging from national to much smaller regions, such as a forest management unit, watershed, or community. Downscaling global scenario data often requires technical skills and modeling capacity beyond those available to many organizations or groups. It may be possible to obtain scenarios that have already been downscaled to an appropriate geographic scale. However, the availability and usability of climate change data and other global projections at the scales and time frames required for adaptation planning are often limited (Kriegler et al. 2010).

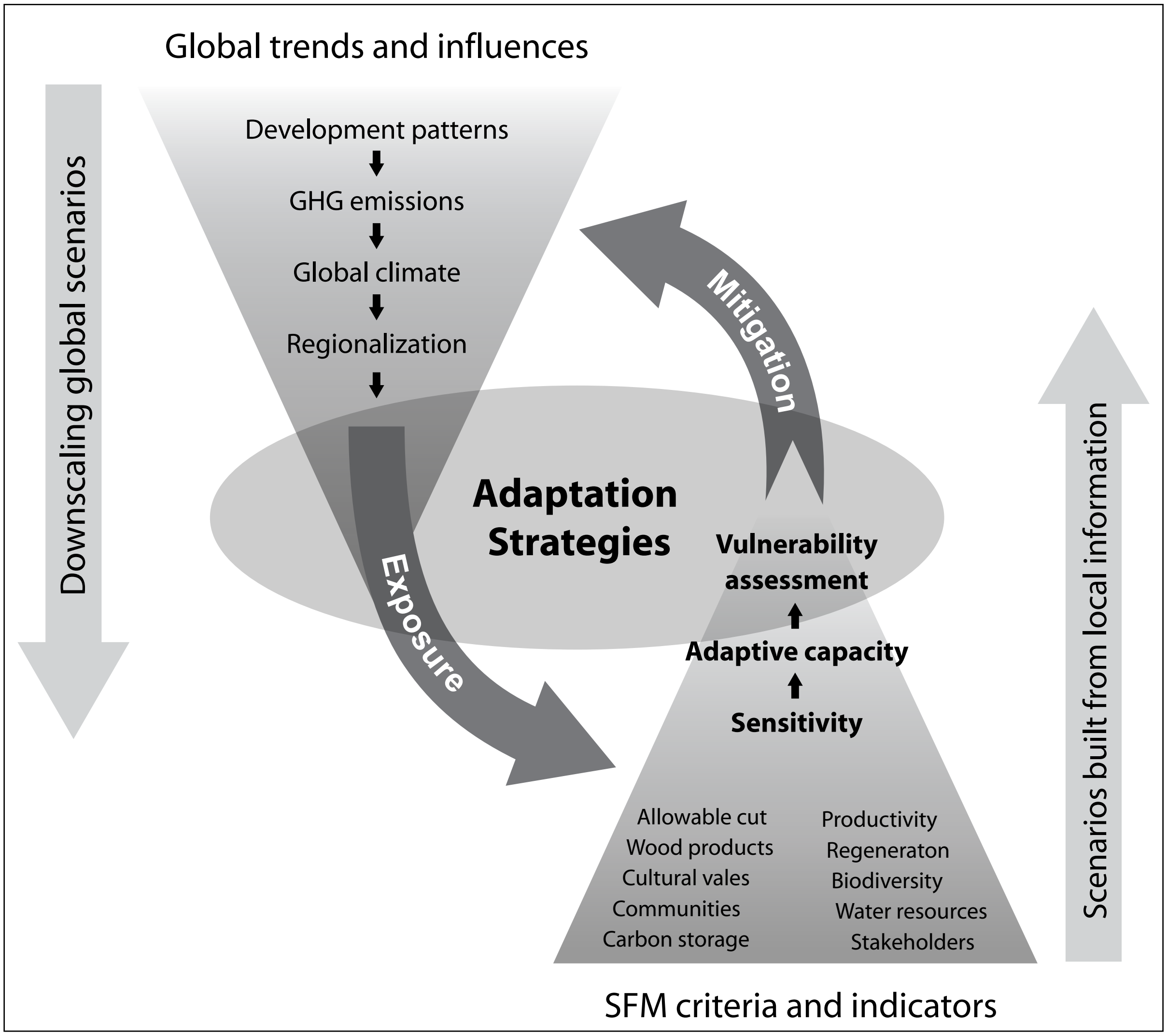

Figure 4. The role of top-down scenarios and bottom-up assessment methods to determine vulnerability, and promote adaptation, of sustainable forest management (SFM) to climate change. Vulnerability of SFM values (represented here by criteria and indicators) is determined by combining potential impacts with local adaptive capacity. Impacts are the combination of climate sensitivity of each SFM value with exposure to climate change. Adaptation strategies can be developed to minimize negative impacts while taking advantage of any positive impacts. Also shown is the potential role of SFM in climate change mitigation. Adapted from a diagram originally developed by Dessai and Hulme (2004).

Local scenarios can also explore the implications of incremental or novel changes in locally important socioeconomic factors. Such scenarios may be developed using ideas contributed by stakeholders, for example, through public participation processes such as surveys, interviews, and workshops. Regardless of the source of scenario information, participatory approaches are increasingly being recognized as an appropriate way to make scenarios more relevant for end users. The local participatory approach will be discussed in more detail later in the report.

Both quantitative and qualitative approaches may be used to determine the impacts of alternative climate scenarios on a system such as an SFM unit. Scenarios of biophysical impacts are generally developed using some form of numerical modeling, but in systems where quantitative relationships are hard to define, particularly where the impacts are societal rather than physical or economic, it may be more useful to interpret the climate scenarios qualitatively. Hence, assessments of regional or local socioeconomic impacts may be informed by global assessments, but typically require biophysical information derived locally, which in turn may be used quantitatively or qualitatively. Some regional and local assessments, including assessments of system vulnerability, may also account for "direct" impacts of climate change on communities and infrastructure (in addition to impacts on forests and the resulting socioeconomic consequences; see dashed lines in Fig. 5). Global and regional socioeconomic trends, such as changes in global markets, economic shocks, and effects of natural disasters, will also be important determinants of local community-scale social and economic conditions, and in particular may affect local adaptive capacity (see Williamson and Isaac 2013).

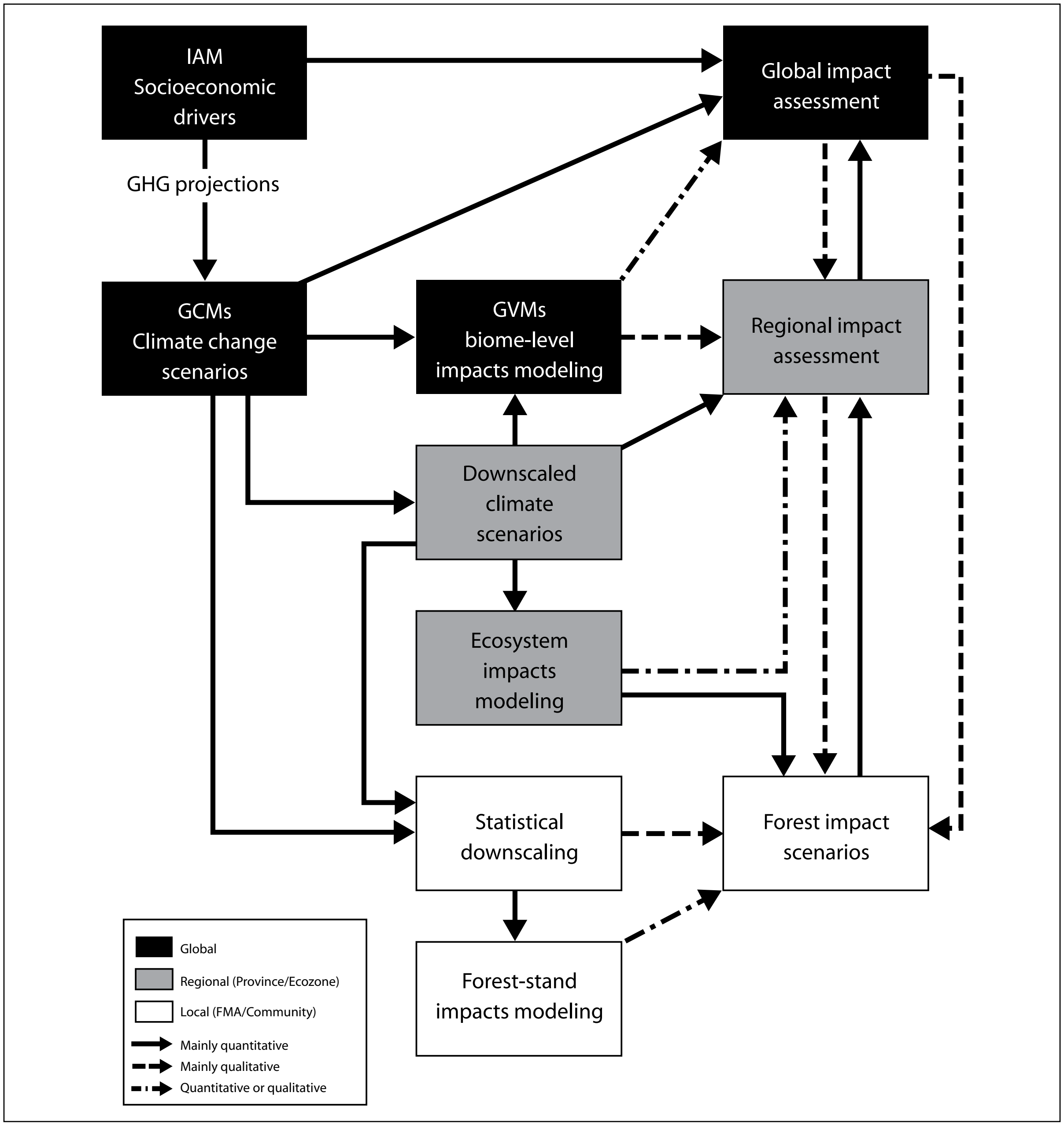

Figure 5. Linkages among scenarios and other sources of information that contribute to a climate change vulnerability assessment for a sustainable forest management (SFM) system. Some information flows are primarily quantitative in nature, indicated by solid arrows; other information flows are generally more qualitative, shown as dashed arrows. The forest impact scenarios (box at lower right) represent the information required as input to a vulnerability assessment applied to SFM. IAM = integrated assessment model; GHG = greenhouse gases; GCM = general circulation model; GVM = global vegetation model; AC = adaptive capacity.

Scenario information can take many forms (quantitative data, trends, qualitative descriptions, images, etc.), and because there are several different methods of assessing impacts of climate change and other stressors, users may need to convert information to an alternative form. For example, quantitative models typically require numerical input data, so modelers will look for ways to quantify qualitative scenarios. Qualitative descriptions (e.g., "large population increase", "falling prices for wood products") can be quantified and represented numerically (10%–20% population increase, return on investment decreases from 15% to 25%), although this may be highly subjective, requiring crude approximations of complex feedback and interaction effects (Shackley and Deanwood 2003). Alternatively, quantitative descriptions of trends and changes could be described qualitatively. Climate change scenarios could, for example, be described numerically (e.g., +3.5 °C warming, 10% increase in annual precipitation, etc.) or in words ("warm and dry", "hot and wet", etc.) or using images (such as landscape maps or horizon visualizations).

Downscaling Global Projections (the Top-down Process)

van Vuuren et al. (2010) suggest that the selection of a downscaling method depends on coverage (i.e., how much of the region is to be included in the scenario), the required spatial scale and resolution, the type of information available, and the purpose of the generated scenario. However, they argue that any method should meet three criteria: consistency with existing local-scale data; consistency with the scenario source; and transparency and internal consistency of the downscaled scenarios. They identify four downscaling methods used to transform global scenarios into country- or grid-level information. These are listed in increasing order of sophistication.

Simple Algorithmic Downscaling

These simple algorithmic techniques convert large-scale projections to smaller scale data. The methods are generally easy to describe, and the results are usually highly consistent with the original data, but they largely ignore local information and have limited ability to represent structural changes (van Vuuren et al. 2010). Three types of simple algorithm are commonly used, each based on distinct assumptions about the relationship between rates of change occurring at smaller and larger geographic scales: proportional downscaling assumes that rates of change will be the same; convergence downscaling assumes that the local rate of change is dependent on, and will therefore converge with, the rate of change projected at the global scale; and scenario-based downscaling assumes that the relative ranking of the system of interest (i.e., compared with other similar systems) will be consistent in the future.

More Complex Algorithmic Downscaling

A more sophisticated approach is to include spatially explicit historical data as a means of "correcting" global scenarios when creating local projections. The rates of change used in this approach are more realistic than those used for simple algorithmic scaling, as they account for different initial conditions and outlooks for growth (Carter et al. 2007). This method has increased internal plausibility compared with the simpler methods discussed in the previous paragraph, because it can reflect structural changes at the local scale and account explicitly for different scenario storylines. One drawback is that this method is often less easy to explain than simple algorithmic downscaling (van Vuuren et al. 2010).

Fully Elaborated Models at Small Scales of Aggregation

Consequences of changes at the local scale may be derived by modeling regional socioeconomic and (or) environmental processes constrained or bounded by larger scale scenarios or models. Such an approach commonly involves the interpretation of global storylines or projections disaggregated geographically or in thematic terms (e.g., for an economic sector or a particular indicator like temperature or GDP) (Rounsevell and Metzger 2010). In their study of climate change impacts on European agricultural land use, for example, Abildtrup et al. (2006) used a systematic and hierarchical procedure of pairwise comparisons based on expert judgment to develop regional socioeconomic scenarios that were then used to drive a land use model. Other methods for interpreting the local implications of large-scale scenarios or storylines include the Delphi method, Monte Carlo analysis, and fuzzy cognitive mapping (Rounsevell and Metzger 2010).

Fully Coupled Models at National or Regional Scales

Global- or continental-scale information can be downscaled to the smaller scale using one of the three methods discussed previously, to obtain a better match between the scale of the forcing data and the spatial resolution at which local-scale processes are represented. Full coupling of this information can be achieved by using the downscaled data to drive dynamic local-scale social, economic, or environmental process models. The output of these local-level models is then aggregated back to the scale of the original large-scale model. The large-scale model can then be run for the next time step (e.g., a year) and the downscaling process repeated.

Accessing Downscaled Scenarios

Reliance on existing scenario data sets is convenient, fast, and can ensure comparability with other scenario-based research. It is necessary, however, to ensure that these scenarios will provide the type of information needed for a vulnerability assessment and that they are focused at an appropriate scale. Information about accessing a variety of existing scenario data relevant to SFM can be found in the appendixes. Appendix 1 contains an inventory of socioeconomic development scenarios. Many of the scenarios reported in Appendix 1 are global in nature and only a few have been downscaled to the national level, so several additional sources of national and regional projections are also listed. Appendix 2 provides information on sources of downscaled climate scenarios applied to Canada. Appendix 3 reviews the types of ecological models useful for determining climate change impacts on ecosystem attributes.

Using Local Information (the Bottom-up Process)

Scenarios of future conditions at a local scale can be constructed by obtaining relevant information about the locally important drivers of change and their impacts. For example, long-time residents of a forested region could provide information about observed changes in climate and forest conditions. Company records regarding events such as major fires or catastrophic floods could also be explored to get a sense of how climate variability has historically affected forest management and operations — and possibly to assess the success of any measures put in place to reduce the impacts of more recent events. Information derived from downscaled global or regional scenarios can then provide a backdrop for understanding the effects of possible future changes. The use of quantitative global projections has been fairly limited in impact, adaptation, and vulnerability assessments to date, with most studies typically examining the local consequences of an assumed incremental change; however, global scenarios are often used to frame discussions of climate change issues at the local level (Kriegler et al. 2010).

The methods mentioned previously (quantitative modeling; empirical analogs; expert judgment; or participatory processes) can be used to explore the possible implications of future changes in key drivers. In general, local specialists and stakeholders are active participants in scenario development, because they usually initiate the vulnerability assessment, and discussion among participants is considered an essential part of the learning process. Dessai and Hulme (2004) suggest that the focus is often more centered on aspects of "social vulnerability" related to the social and economic well-being of communities rather than those of "physical or natural exposure" that are usually the central concern in the top-down process. SFM may be rather different, however, in that the impacts of physical or natural exposure to climate change will operate directly on the forest resource. Hence, stakeholders' knowledge of potential biophysical impacts and ecological responses will be key to developing locally useful scenarios. The bottom-up process may lead to the creation of local scenarios that contain or use information derived from other methods such as modeling or analogies, but participatory discussion is often the preferred method because it can support collective learning and action (Williamson et al. 2007).

Some of the benefits of the participatory approach to scenario development include opportunities for social learning; increased relevance and local detail in the storylines; and development of problem-solving skills for the key players. All of these benefits can lead to greater legitimacy at the local scale and hence more buy-in among the participants (Rounsevell and Metzger 2010). Bizikova et al. (2009) for instance, find that participatory scenario development encourages stakeholders to think more about the future and its impacts on the local community, incorporating lessons learned from past events and community responses, and drawing attention to possibilities for future adaptation. This then provides opportunities for the combination and integration of development plans, while balancing the need for adaptation to climate change with other priorities. Hence, Bizikova et al. suggest that participatory scenario development is most effective when information about the biophysical impacts and risks of climate change is balanced with that regarding social impacts and risks and other issues of local importance, and when stakeholders are involved in identifying local responses to the combined challenges of adaptation and socioeconomic development. Developing robust adaptation strategies from a set of clearly thought-out scenarios also requires a long-term vision while identifying short- and long-term actions to enable adaptation to achieve that vision (Bizikova et al. 2009).

Participatory scenario development is also thought to improve collaboration and consensus building, increase planning and organizational capacity, and support local empowerment. For example, Evans et al. (2008) argue that participatory scenario development can improve collaboration in the use and management of forests where decision-making power has been delegated to communities. They found that participatory scenario development improved collaboration and negotiation among communities and local authorities and helped marginalized groups, as well as community leaders, become more assertive and candid in discussions and decision making. This led to broader group participation in the planning process and to the development of strategies that encouraged self-sufficiency and intracommunity collaboration. Forest-based communities were able to assume more responsibility for control over forests and were also encouraged to self-organize in ways that allowed them to benefit from the opportunities provided by decentralized forest governance.

Perhaps most importantly, stakeholder participation has been found to lead to important and surprising insights that contribute to the development of more appropriate policies (Rounsevell and Metzger 2010). Evans et al. (2008) call these instances “break-through moments”, where exposure to different perspectives and ideas allows for creative thinking and the development of alternative solutions, often better suited to the problems confronting managers and communities.

Bizikova et al. (2009) discuss some of the challenges with participatory scenario development including how to link quantitative information on current trends and projections with qualitative information, and how to transform scenario implications into policy. For example, additional effort is needed to maintain dialogue among researchers and local groups on the challenges and uncertainties of projections, and information must be shared to address adaptation and development in the face of uncertainty. Rounsevell and Metzger (2010) also caution that participatory scenario development can have limited credibility when the participant groups are not representative of all stakeholders, if there are substantially different perceptions about how the system operates, or if the created scenarios are not internally consistent. Additionally, Evans et al. (2008) note that participatory methods are less effective when facilitation skills are lacking or when some participants feel threatened by the participation of others. These issues indicate that careful facilitation and planning can be crucial to successful participatory scenario development.

SCENARIOS FOR SUSTAINABLE FOREST MANAGEMENT

As previously described, scenarios have been used to investigate the possible future development of many different types of systems at a range of scales. Toth (2003) suggests that scenarios should be developed to provide enough information to be useful, but that they should not be overly deterministic in identifying the conditions or processes best chosen by end users. Following Toth, the term "SFM scenarios" is used here to describe scenarios that could be created to suit the needs of various end users involved in SFM. Development of multiple scenarios of future impacts is a key element of the CCFM vulnerability assessment framework for SFM (Williamson et al. 2012). Typical SFM scenarios might explore changes in the ability to maintain or enhance biodiversity, water storage, or carbon sequestration, as well as economic, social, and cultural benefits, including employment, forest sector profitability, health and safety in forest-based communities, or recreational opportunities, among many others.

Depending on the impacts of interest, the most important and critical drivers would be chosen and used to develop SFM scenarios. Increasingly, vulnerability and impact assessments explore the impacts of climate change while also examining the effects of other important driving factors on the outcomes of interest, as there is recognition that climate is not the only thing that will change and that decisions about adaptation, mitigation, and development are made in the context of multiple stresses (Cohen and Waddell 2009). While such assessments better reflect the actual contexts in which decisions are made, they also tend to be less certain owing to their greater complexity and the potential for unexpected interactions amongst different driving forces. There is also a challenge in choosing a limited, manageable, and coherent set of scenarios that address the many factors relevant to a specific context (van Vuuren et al. 2011).

As depicted in Figure 6, the following discussion focuses on climate change as the critical driver affecting SFM, although many other factors are recognized as being important to the future state of SFM, and carrying out a scenario analysis is a good opportunity to investigate these other factors (e.g., Mora et al. 2013; also see later discussion of the Millar Western cumulative impacts study). Climate change scenarios are described first, as these are often the central driving force explored in a vulnerability assessment. Next, biophysical scenarios are discussed, including possible tools for assessing climate change impacts and potential sources of information. Other drivers of change that may be relevant to future biophysical conditions are also highlighted. Finally, socioeconomic scenarios used to understand the potential social and economic impacts of climate change are reviewed. This review includes a short description of how socioeconomic and climate change scenarios can be developed to assess the impacts of both types of drivers on aspects of an SFM system.

Scenarios of Climate Change

The output from GCMs is rarely directly suitable for local-scale impacts assessment. Instead, projections of future climate are generally downscaled to regional or local scales. Regional-scale climate data are often produced by some form of spatial interpolation of the coarse-resolution output, or by dynamical downscaling methods, as characterized by regional climate models (RCMs). Results from GCMs may also be applied locally using other methods, summarized in Figure 5 as "statistical downscaling".

In the past decade, the online availability of climatological data and model projections of future climate has exploded, largely because of international efforts to support climate change studies for the IPCC process, coupled with the expansion of the Internet. Most scenarios of future climate used in impacts assessment are derived from GCM projections, but much useful information can be gained about potential impacts on forest ecosystems and SFM using simpler approaches. A good example is to add incremental changes (e.g., 1, 2, and 3 °C)

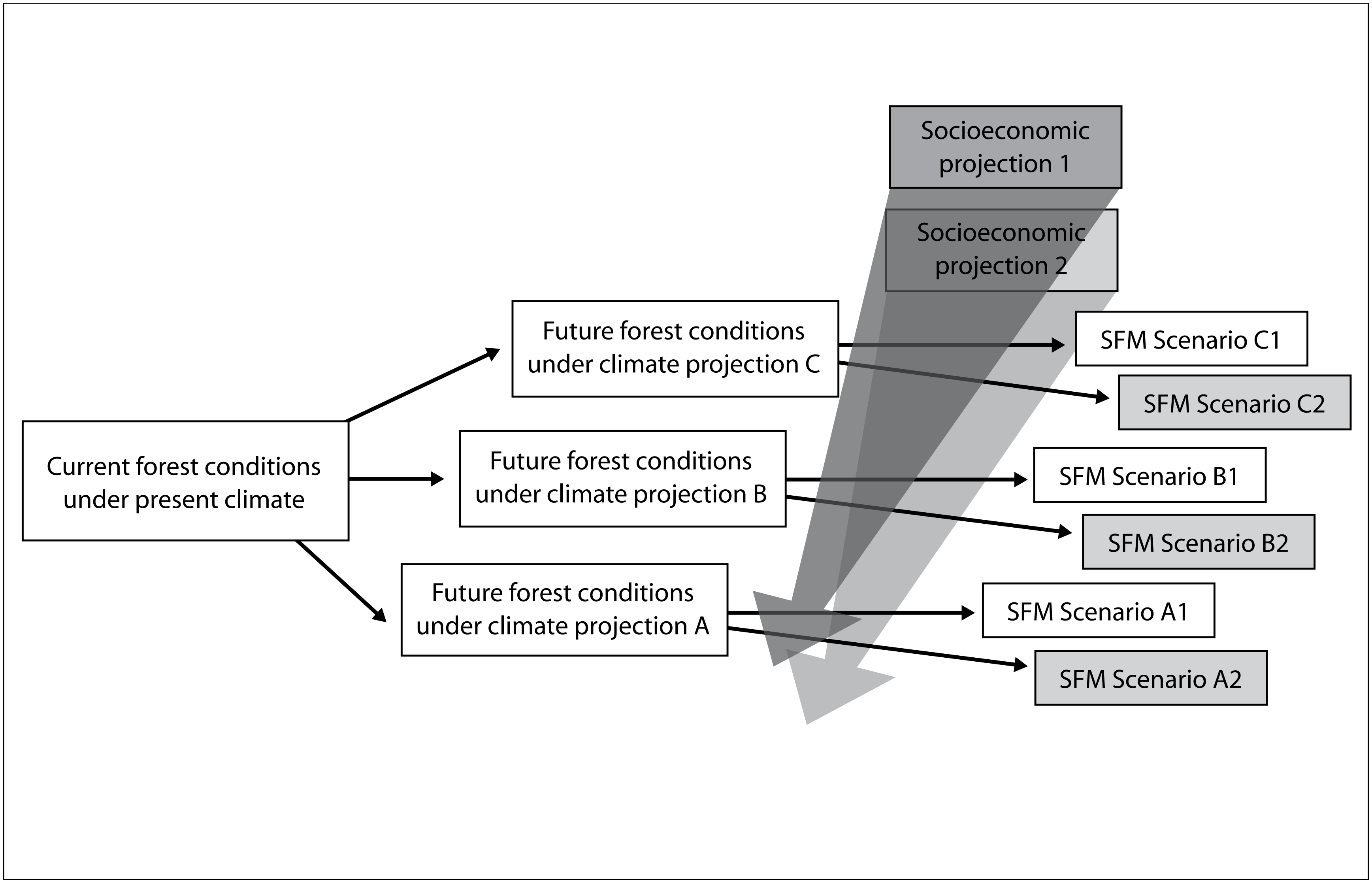

Figure 6. Creating multiple scenarios of the interacting effects of climate change and socioeconomic change on sustainable forest management (SFM).

to observed historical temperature data, coupled with fractional changes (e.g., –5%, 0%, +5%, or +10%) to historical precipitation data. Information about the expected rates of change (e.g., 4 °C warming per 100 years), and an assumption that seasonal and inter-annual variability will not change dramatically during the period of the scenario, may be sufficient for assessing potential impacts without requiring data obtained from a climate model. A caveat to this approach is that some combinations of temperature and precipitation change are less plausible (e.g., decreases in mean precipitation may be more likely than increases with warming in a specific region).

Another method is to use spatial or temporal analogs of future climate. Barrow (2001) explains that the objective is to find a recorded climate regime (which could be the mean climate or some extreme event) resembling the possible future climate at the location of interest. Spatial analogs generally use the climate in a climatically warmer location (generally at lower latitude or lower elevation). It is important to recognize, however, that some attributes of the two locations may not be comparable, such as the annual cycle of changes in day length, soil types, and geomorphology. Temporal analogs use past periods of warmer conditions at a specific location to characterize how the climate may change in the future. Of these, Barrow (2001) suggests that instrumental analogs (i.e., based on meteorological measurements) are more useful for constructing future climate scenarios, because they are available at appropriate temporal and spatial scales and because the observed data should be internally consistent and physically plausible. However, there is little likelihood of finding extensive instrumental data from past warmer periods in much of rural Canada, where the climate station network was relatively sparse until the 1950s. Climate anomalies during the past century are thought to have been fairly minor compared with anticipated future changes. For example, the drought conditions that led to the Dust Bowl era of the 1930s have been observed at comparable scales in recent years, though their effects may have been less catastrophic owing to improved land management practices.

Alternatively, it may be possible to obtain paleoclimatic information that provides some insight into how local ecosystems would respond to warmer conditions in the future. Paleoclimatic reconstructions are often built on very sparse data, and there is often considerable uncertainty about their quality (e.g., paleontological data obtained from different sources may not be sufficiently close in time and space to provide an accurate picture of the climate and its impacts). It is also generally true that paleontological data with the greatest spatial and temporal precision will be from the most recent past and therefore represent past climates that compare with the low end of the range of anticipated future climatic warming.

Advantages of using scenarios derived from GCM projections include the assumption that projected changes in different climate variables should be physically consistent, meaning that they result from basic principles of mass and energy conservation that are respected in any physically based model. Internal consistency also means that possible shifts in the relationships of these variables over simulated time are derived physically rather than being guessed at or ignored. Moreover, insofar as GCMs are able to project spatial and temporal trends in future climate, the derived scenarios capture these trends and hence relate them to a particular region or time period. This may be particularly important when assessing the timing and locations of potential impacts for adaptation planning.

GCMs are the primary source of spatially explicit data needed to assess the possible effects of climate change on ecosystem composition, structure, and function and on human infrastructure and associated activities. At the global scale, there is general agreement among GCMs that greater warming will occur over land than over the oceans and that greater warming will occur at higher latitudes (IPCC 2013). Projected increases for northern continental North America are therefore comparatively large. Price et al. (2011) examined the results for Canada and the continental United States from four GCMs forced by a range of GHG emissions scenarios (SRES A2, A1B, and B1 as recommended by IPCC in the AR4). They found that the GCMs were consistent in projecting that the greatest warming will occur in the far north (increases of 5–10°C for annual mean daily minimum temperatures by 2100), and the least on the east and west coasts (3–5°C for annual mean daily minimum temperatures by 2100).

Much of the range in these projections was a consequence of the GHG forcing assumed in individual GCM projections (i.e., B1 < A1B < A2). However, present-day trends in atmospheric GHG concentrations have exceeded the worst-case emissions scenarios prepared by the IPCC in AR4 (e.g., Le Quéré et al. 2009). Furthermore some warming, and its various effects, is inevitable over the next few decades because of recent increases in atmospheric GHGs and the lagging thermal response of global oceans. Price et al. (2013) concluded that for most of Canada's forested regions, annual mean temperatures are very likely to increase by at least 2º C by 2050, compared with ca. 2000.

Rising temperatures will cause increased evaporation of water from oceans, lakes, and vegetation and hence higher humidity, leading to generally increased annual precipitation of about 1%–2% per degree of warming (Hengeveld 2006; Trenberth et al. 2003), although mean effects at local scales can vary from small decreases to much larger increases. Price et al. (2011) found that GCM projections of changes in precipitation for Canada were less consistent spatially than those for temperature generated by the same models. However, the GCMs agreed that there will be increases in mean annual precipitation for most of the country; that these increases are related to the amount of warming projected; and that the largest increases (in relative terms) will occur in the far north. In general, the mean increases in precipitation projected by the GCMs cannot be sufficient to offset the overall increase in potential evapotranspiration due to rising temperatures. Hence, increased frequencies and intensities of drought events are to be expected, particularly in regions such as the Canadian Prairie provinces, where current annual precipitation is already limited compared with potential evapotranspiration (e.g., Hogg et al. 2008). Increased temperatures will also accelerate the melting of glaciers, a process that has been in evidence worldwide for much of the 20th century. In western Canada, the imminent disappearance of glaciers in the southern Rockies could lead to general shortages of freshwater, presently used for human consumption, crop irrigation, and oil and gas production.

Price et al. (2011) found some evidence of seasonal shifts, often towards wetter, and in some regions sunnier, summers, which indicates a trend towards fewer but more intense precipitation events (e.g., Trenberth et al. 2003). Indeed, many of the increased risks due to climate change are anticipated to result from changes in the frequency and intensity of extreme events (e.g., occurrence of severe floods and large wildfires) that can cause widespread change to ecosystems and damage to human infrastructure. Because the atmosphere is a chaotic system, however, the timing, magnitude, and locations of such extreme events will never be predicted by GCMs. In practice, the potential for increased occurrence can be assessed by superimposing recently observed variability on the projected long-term trends. Inferring changes in the extremes from changes in the variance of modeled mean values may also be possible, but climate scientists will attach considerable uncertainty to these estimates. Kharin and coworkers (Kharin and Zwiers 2005; Kharin et al. 2007) have led much of the effort to interpret GCM projections of changes in extremes and variability. They have found that greater warming generally produces greater extremes in both temperature and precipitation, but with considerable spatial variation around the mean global trend. Bouwer (2011) even suggests that GCMs may be the only means to infer changes in the occurrence of extremes in the near future, because such changes are difficult to observe in the shorter term against a background of natural variability.

Examples of changes in the frequency and (or) intensity of other climatic extremes that may be evident from GCM projections include

- heat waves, particularly those affecting major urban centers in southern Ontario and Quebec, with serious implications for public health
- extended droughts, arising from more frequent occurrence of sequences of years where annual evapotranspiration approaches annual precipitation (see Dai 2011)
- severe storms, particularly from hurricanes in the tropical Atlantic tracking northward to the Canadian Maritime provinces
- El Niño events, causing generally warmer and drier conditions on an approximate 4-year cycle, particularly in western North America

It is important to recognize that the expectations of more extreme climatic and meteorological phenomena may not be confirmed by observations, either in the recent past or during the near future, i.e., considerable uncertainty exists. The IPCC (Field et al. 2012) produced a comprehensive review of worldwide historical observations of extreme events. Extreme events are rare, by definition, and the overall sparseness of data, both geographically and in the historical record of observed events, makes it difficult to detect long-term changes in their frequency and (or) intensity. Nevertheless, Field et al. (2012) report that there is evidence of human activities, including increases in atmospheric GHG concentrations, causing increases in extreme climatic events. In particular, there is "medium" confidence that the duration and frequency of warm spells and heat waves have increased in many regions of the world and that the intensities of drought events have also changed (notably, droughts appear to have become less frequent, less intense, or of shorter duration in the conterminous United States).

There is also medium confidence that extreme precipitation events have become more intense at the global scale. However, determining a climate warming signal in the magnitudes and frequencies of flooding events is more challenging, because long-term hydrological records are lacking for many watersheds and because ongoing changes in land use and water supply management confound any trends detectable in the available data. Hence, Field et al. (2012) report little agreement in the hydrological records and no clear trends in the occurrence of flooding events.

Biophysical Scenarios

Several methods can be used to estimate the ecological impacts of climate change to provide information critical to assessments of future vulnerability for SFM (see Fig. 4). Sources of information for creating forest impact scenarios include anecdotal observations and monitoring programs, as well as projecting future changes using various types of models.

Given that climate scenarios are typically available as numerical data sets, they can be used as forcing data to drive climate-sensitive models of forest ecosystem dynamics. The term "climate sensitive" means that the projections from ecological models are dependent on the climate data used as input, though the algorithms that capture this response linkage may range from simple to complex. "Ecosystem dynamics" refers to several ecosystem processes, including growth, competition, and mortality as distinct components of stand development and succession, and the effects of natural disturbances. In the forest carbon cycle, ecosystem dynamics denotes the roles that these processes play in the flow of carbon among vegetation, litter, and soil pools, as well as exchanges between ecosystems and the atmosphere.

While considerable research effort continues to be invested in exploring potential impacts of climate change on forests, it is likely that in some regions, land use pressures could be even more important in determining future forest conditions. These include urban expansion into rural areas, conversions of land to and from agriculture, and the impacts of exploiting deposits of minerals and fossil fuels (e.g., Yamasaki et al. 2008). Impact and vulnerability assessments could be used to explore these combined effects of changes in climate, soils, and topography on the future state of forests, particularly at local to regional scales. Cohen and Waddell (2009) report that there are few examples where both scenarios of climate change and land use change have been used to understand impacts to ecosystems — largely because relatively little effort has been invested in developing land use change scenarios. One notable exception is the Advanced Terrestrial Ecosystem Assessment and Modelling (ATEAM) assessment carried out for the European Union (Schröter et al. 2005). This assessment accounted for projected changes in land use and forest management linked to the IPCC SRES scenarios, in addition to changes in climate. A stabilizing population in Europe and technological advances were found to reduce the land area needed for agriculture, allowing land to be used less intensively, for bioenergy production, or to increase the forested area. The ATEAM assessment also concluded that forest management decisions may have a potentially greater effect on future wood production than either climate change or land use change, but these impacts will be largely dependent on the future value of forest products driven by global markets.

Observations: Using Spatial and Temporal Analogs

Although models are often favored as the means to project changes in forests as the climate changes, it must be recognized that current-generation ecological models are far from perfect, and other methods of projecting forest changes exist. It is relatively easy for forest scientists and managers to make personal observations of how the range of climatic or microclimatic zones found in a forested region (related to latitude, elevation, topography, and soils) are correlated to the occurrence, growth rates, and competitive success of different tree species. Much research effort has been invested in recent years within most provinces to develop ecoclimatic classification systems, which facilitate understanding and can underpin forest management prescriptions. Clearly, such information can be used by local managers to infer how systematic changes in climate (e.g., warmer, drier, wetter) are likely to affect the future distribution, composition, and productivity of forests in that region. This approach is a form of using present-day observations of spatial variation as a proxy for the effects of future climate trends. GCM scenarios might be consulted to carry out simple what-if analyses. They could also form the basis for adaptation planning, at least for a few decades. Almost as important is that this kind of information can be very useful for assessing the plausibility of projections generated by biophysical models.

Using past impacts of climate change on forest ecosystems as an analog for potential future impacts is more challenging. While much is known about how ecosystems have changed over the last few millennia in response to natural variations in climate, the data are generally highly technical and limited mainly to information about forest species composition and distribution. The processes driving past changes were relatively slow and active long before humans began to have significant impacts on forest succession. Changes in productivity related, for example, to variations in temperature can be estimated from tree-ring records, but even here there are many confounding factors (such as moisture regime and insect activity), and there is much uncertainty about what the data really show (e.g., see recent review by Brienen et al. 2012).

Anecdotal observations capture much of what is known about the impacts of climate change, particularly in remote communities in central and northern Canada. Williamson et al. (2008) noted that reports gathered from interviews with life-long residents in remote rural regions have helped scientists to assemble an increasingly coherent picture of the effects of changes in climate on local ecosystems and communities. Confirmation that change has actually occurred has attracted interest from the media and politicians, hence raising public awareness of the potentially greater impacts of anticipated future changes.

Monitoring programs are systematic efforts to collect data and information over time, which enables jurisdictions to assess change in the status of natural assets, particularly those likely to be affected by global change. Monitoring informs ecological stewardship, including SFM. For example, within managed forests, permanent sample plots, properly maintained and remeasured at regular intervals, provide records of tree growth over multiple decades, which may be critical for reconstructing responses to historical climate. Because Canada is a large and sparsely populated country, however, and because of the low productivity of many of its forests, long-term monitoring programs are relatively expensive and difficult to establish and maintain, which makes detection of meaningful trends from permanent sample plot data challenging.

Canada's National Forest Inventory (https://nfi.nfis.org/index.php) is a new initiative of provincial and territorial jurisdictions and the federal government, coordinated by Natural Resources Canada (Canadian Forest Service), under the auspices of CCFM. The National Forest Inventory provides a national network of permanent sample plots established on a systematic 20 km grid, including unmanaged forest regions. Sample plots are measured using standardized methodology, including soil sampling and tree core extraction. Data from individual plots will be scaled up to larger areas using remote sensing algorithms validated against the plot-level measurements. Assuming that the plots are remeasured periodically, the Canadian National Forest Inventory program will provide for more rigorous analyses of historical growth trends, as well as future growth rates and their correlation to climate, than has ever been previously possible at a national scale.

Long-term monitoring to detect actual changes in climate and in ecosystem composition, structure, and function is critical for

- assessment of ecological and economic impacts, e.g., insect and disease outbreaks
- accurate reporting of gains and losses, e.g., in forest area and biomass stocks
- development, improvement, and validation of models to make future projections

Intensive field experiments, though funded for relatively short periods, involve many scientists. An outstanding recent example is the Canadian Carbon Program (formerly the Fluxnet-Canada Research Network, FCRN; e.g., Coursolle et al. 2006), which has provided more information about boreal ecosystem functioning in a 15-year period than was ever known previously. This program should lead to greatly increased capacity to model future changes, including the effects of natural disturbances, in a range of Canadian forest ecosystems. The data obtained are also crucial to the development and improvement of ecosystem process models needed to project both small- and large-scale impacts of climate change on Canadian forests.

An ecological process model tested at a few sites where natural processes (e.g., growth and respiration of a particular tree species) have been studied in great detail should be applicable to the same species growing at a wider range of sites — or in the changed environmental conditions expected in the future. Ideally, such tests will be carried out for a complete range of environmental conditions so that the model can be used with some confidence over a larger region. Hence, validation over a large spatial domain also increases confidence in the model's capacity to simulate responses to changes in climate over time. This modeling approach comes with a big caveat, however: none of these models are perfect and many uncertainties will remain in the results they produce.

Volunteer science monitoring programs at provincial to national scales, coordinated by agencies such as Environment Canada in collaboration with nongovernmental organizations and university research groups, can generate important data and support the development of local indicators of change. For example, PlantWatch projects (http://www.naturewatch.ca/english/plantwatch/) now operate in every Canadian province and territory, enabling volunteers to contribute standardized information on dates of initial and maximum blooming and leaf emergence.

Williamson et al. (2008) note that some volunteer programs have continued long enough to provide definitive evidence of long-term changes, including climate impacts. In much of western Europe, for example, amateur and professional botanists have recorded leaf-flushing and flowering dates for numerous plant species for well over a century. Recent work, notably in Germany, has used this type of information to demonstrate significant increases in mean growing season length (e.g., Menzel et al. 2006). Similar results have been obtained in Canada through PlantWatch, though for shorter periods (e.g., Beaubien and Johnson 1994; Beaubien and Hall-Beyer 2003; Beaubien and Hamann 2011).

Ecological Models

Although scenarios of future climate are easy to obtain from numerous sources (see Appendix 2), published scenarios of future forest impacts are rare. The reasons for this include the need to use properly parameterized and appropriate ecological models; the location-specific nature of ecological projections; and concerns about model accuracy. Many models of forest growth have been constructed, the earliest probably being stand yield tables that have their origins in 19th century European silviculture. However, it is only in the past 40 years or so, with the increasing availability of powerful computers, that models of greater complexity have been developed and applied over large areas, ranging from single stands to forest management units to continents.

Forest ecosystem models can be broadly divided into those that are empirical (statistical) and those that are mechanistic (process-based). While some are focused on single forest species, there are many others that attempt to simulate all the dominant species as a simplistic representation of a functioning forest ecosystem. In general, projecting the effects of future climate changes will require a climate-sensitive model. Some statistically based models use relationships between present or historical climate and present-day tree species or forest status to infer how attributes (such as species distribution) may change in the future. Conversely, many (but not all) mechanistic models capture responses to climate, to simulate environmental effects on ecosystem processes, including growth and competition among species. A recent and highly accessible review of ecological models is provided by Glick et al. (2011). Some in-depth discussion of ecological models and their various strengths and weaknesses also appears in Johnston et al. (2010a) and is summarized in Appendix 2.

Selecting Scenarios of Climate Change Impacts on Forests

As Johnston et al. (2010a) note, assessing climate change impacts on forests is an inexact science. No single approach can provide all the answers, and a combination of contrasting methods may give more reliable insights. In particular, computer models cannot capture all of the interacting processes that affect ecosystem responses to climate variation and climate change, so the projections obtained from any ecological process model should be treated with caution. In general, it is good practice to use at least two, preferably three, different models (ideally of different types, insofar as they can all provide useful data) and to drive each of them with more than one climate change scenario (i.e., as created by different GCMs and (or) forced by different scenarios of GHG emissions).

Regardless of the assessment method, it will be important to select two or more forcing climate scenarios, ideally generated by different GCMs. The selection should respect several criteria, as listed by the IPCC Data Distribution Centre (http://www.ipcc-data.org/ddc_scen_selection.html), which can be summarized as follows:

- Is the projected increase in global mean temperature consistent with the generally accepted range by 2100? (From AR5, this is considered to be 0.3–4.8 °C, corresponding, approximately, to a range of 0.5–9.5 °C for Canada, depending on the GHG emissions scenario selected.)
- Are changes in different climate variables over time and space physically plausible and consistent?
- Are the required projected variables available and reported at spatial and temporal resolutions that are useful to the planned impact assessment?
- Are the scenarios representative of the range of climate projections for the region of interest?
- Are scenario data easy to obtain, interpret, and apply to the impact assessment?

Murdock and Spittlehouse (2011) provide more detail on selecting scenarios of climate change for use in British Columbia, though the principles are applicable in all parts of Canada. As explained previously, climate scenarios should not be considered predictions, particularly when focused on specific locations. In addition to any inaccuracies in the downscaling method, downscaled climate scenario data necessarily carry with them all of the uncertainties built into the GHG forcing assumptions, as well as the limitations in the GCM. The further we project into the future, or the more closely we tie the projection to a particular location, the greater becomes the uncertainty. The Canadian Climate Change Scenarios Network (CCCSN) website provides a useful scatterplot tool that allows the differences among GCM projections of many climate variables to be examined at specific locations for different future periods (see Appendix 2).

Price and Scott (2006), working with expert modelers, found that when two well-established (and widely published) dynamic vegetation models (DVMs) were applied to North American forest ecosystems and driven by identical climate scenario data, the projections obtained were extremely different. The inherent differences between the two DVMs created differences in the simulated responses to climate warming that were far greater than the differences attributable to different GCMs forced by different GHG emissions scenarios. This may be an extreme example, but the surprising results from this particular study demonstrate the importance of investigating multiple models and forcing scenarios before developing any confidence in model projections. In general, it is necessary to use more than one ecological assessment model and to treat all simulation results with caution. (Conversely, if two or more models agree substantially in their projections, this does not necessarily mean they should be believed.) Validation of such models using past observations from local sites is crucial to building confidence in model projections for the future.

Loehle (2011) suggests few ecological modeling studies actually meet the criteria needed to make meaningful impact assessments. Basic requirements include using multiple climate scenarios from more than one current generation GCM and validating both the climate model and the ecological model against observations. Other factors include accounting for the effects of increasing CO_2 concentration on plant productivity; considering transient as well as equilibrium (long-term) responses of the ecosystem; and assessing the predictive "skill" of the GCM and the ecological models being used. It is important to recognize limitations in the models and to use their results with caution. For example, model results may be unrealistic in absolute terms, but the trends they project over time may still be plausible. For sustainable forest management questions, the most useful diagnostic outputs from ecosystem models are likely to be species composition, productivity, and carbon stocks (including those contained in woody biomass). In regions prone to drought, estimates of water use (evapotranspiration) and its effects on seasonal and annual soil water balances will also be important.

A major challenge in vegetation modeling is accounting for spatial variability, due to varying soil characteristics, as well as latitudinal and topographic effects on climate and east–west gradients in continentality (referring to the balance of coastal and midcontinental influences on climate). Regardless of the type of model used, assessing climate change impacts on an ecozone or a forest management area generally requires "spatial data", which may include information on soils, forest species composition and the history of natural disturbances and human management, as well as climate.

When developing and (or) using any model for impact assessment, it is important to meet the criteria provided by Loehle (2011) and also consider the following questions:

- Does the model provide estimates of changes in indicators of interest?
- Is the model well tested and are results published in peer-reviewed literature?
- Is expertise available and is there access to computing facilities suitable for operating the model?
- Are necessary input data sets, including climate data and climate scenarios, available and in the correct format for use with the model?

Before using a model to create an impacts scenario, it should be validated where possible against observations. For example, how does the spatial variability in the simulated forest for the present day (or closest future time slice) compare with what is known of present-day spatial variability (e.g., in species composition and productivity)? Are projected changes in key forest attributes, such as species composition and wood volume, too rapid to be plausible? Are there abrupt changes in the simulated forest correlated with distinct events (or rapid changes) that appear in the climate data? Any obvious discrepancies should be investigated and discussed. In many cases, mistakes will need to be corrected and (or) model parameters will need to be adjusted and the runs repeated.

Only after the model results have been assessed for plausibility should they be used, for example, to estimate changes in timber supply and other forest benefits and hence to assess the possible consequences for local industries and communities (e.g., Williamson et al. 2008). Models may be used to investigate the effectiveness of changes in forest management practices as adaptations to climate change. For example, Steenberg et al. (2011) used the LANDIS-II model to assess different adaptation treatments, singly and in combination, applied to a 14 000 ha forested watershed in Nova Scotia. They concluded that multiple adaptation strategies are likely to be required to facilitate forest transitions in a changing climate, to minimize the disruption of the supply of goods and services while maintaining a diverse and healthy forest. Other examples include the use of climate envelope models to change the species selected for reforestation and to modify seed transfer policies (e.g., see Pedlar et al. 2011), or to implement protection against fires and other disturbance factors. It will always be important to recognize the limitations of impact models, however, and to apply appropriate levels of uncertainty to any model predictions. For example, if two equally plausible models project productivity estimates that differ by ±25% of the mean, then this uncertainty should be carried through to calculations of projected changes in harvestable timber and added to any other uncertainties in the calculation of allowable cut (such as a range of possible losses from wildfires).

What Do Biophysical Impact Models and Scenarios Tell Us?

Johnston et al. (2010a) review what can be learned about the future of forest species in Canada, based on results reported from different types of ecological models (see also Appendix 3). It is important to appreciate that all models are approximations of reality. In the case of ecological models, many important details governing responses to changes in climate will not be captured. Nevertheless, some consistent messages have been obtained from recent modeling studies.

Climate envelope models (CEM), correlate the present-day distributions of individual tree species to the boundaries of distinct climatic zones, and then project how these boundaries would change with different scenarios of future climate. Examples include the work of Iverson et al. (2008), Hamann and Wang (2006), and McKenney et al. (2007). These models have been used successfully to predict the spread of invasive species (e.g., insects and noxious weeds that can spread rapidly and adapt quickly to new environments), and also the northward expansion of tree species following deglaciation, when compared with pollen records. However, CEMs lack representation of growth and reproductive cycles, which limits their value in projecting changes in distribution of forest trees in a rapidly changing climate. Insofar as northward shifts of species' climatic zones are generally expected, it is clear that even with the most conservative projections, tree species or genotypes that are presently restricted to small geographic ranges will be unable to naturally colonize new areas fast enough to maintain viable populations. McKenney et al. (2007) tried to allow for the effects of barriers to forest migration by comparing simulations with a CEM for North America, where the future climate zones were either unlimited by colonization constraints (termed the full-dispersal scenario) or entirely constrained (the no-dispersal scenario), and future ranges were limited to those overlapping the current range. With full dispersal, most future species ranges would shift northwards by 700 km, with areas decreasing on average by about 12% (though ranges for some species were projected to increase). With no dispersal, the northward shift would be limited to about 330 km, and the mean range area would contract by 58%.

McKenney et al. (2007) concluded that a warmer climate in Canada would favor increased tree species richness, because many species presently limited to the United States would find climatically suitable zones, particularly in eastern Canada, by 2100 (i.e., if seedlings of these species could be established). Projections of future species ranges resulting from climate scenarios forced by the more extreme SRES A2 GHG emissions scenario shifted the climate envelopes further north and reduced their areas more than those obtained from the more benign B2 scenario.

Forest gap models, first developed by Botkin et al. (1972) and Shugart (1984), include dynamic representations of stand-level processes. These models enable somewhat realistic projections of how forest composition and other attributes (such as growth rates and woody biomass accumulation) can change over time and in response to changes in climate and other factors, such as CO_2 concentration. They are well-suited to application at specific sites, so they can be validated at locations where detailed environmental data are available. Many traditional gap models are similar to CEMs in not accounting for regeneration constraints on range expansion, instead making the implicit assumption that propagules (i.e., including vegetative reproductive structures as well as seeds) of all species (within a set defined for the region of interest) are present in all locations. This can lead to implausible results when a gap model is applied over a large region in which some species are absent from colder sites at high latitudes or high elevations. Some newer gap models do attempt to address this limitation, making them better suited for climate change impact studies (see Price et al. 2001 for a review of this topic). Several studies have been carried out for Canadian forest ecosystems using gap models (see Johnston et al. 2010a). Recently, it has become possible to use these models to also project changes in forest composition over large regions (e.g., see Shuman et al. 2011).

In reality, it is expected that the reproductive strategies of some species will favor their rapid dispersal and colonization, while species producing large seeds, or restricted to vegetative propagation, will be disadvantaged (e.g., Price et al. 2001). The general trend will be for vulnerable species to become increasingly maladapted to the changed conditions, causing reduced forest productivity and tree survival, leaving only the more widespread and adaptable species to survive and colonize at higher latitudes and (or) higher elevations. In many areas, natural tree migration will be further impeded by barriers that include poor soils, large lakes, urban and industrial landscapes, and extensive agricultural regions.

Further, a warmer, drier climate is likely to result in generally more frequent and intense natural disturbances, notably wildfires (e.g., Flannigan et al. 2009) and destructive insect pests. The effects of climate warming on insect populations are complex, however, and may result in reduced outbreaks of some pests in some areas (e.g., Candau and Fleming 2011). In general, increased natural disturbances have the potential to cause large losses of timber and potentially serious economic impacts on forest-based communities. Losses of some species characteristic of old mature forests (including insects, small mammals and other animal taxa, as well as nonvascular plants) are also likely to be accelerated by more severe disturbances, though pioneer species may benefit when colonizing disturbed areas (e.g., Thompson et al. 1998; Bernhardt et al. 2011).

DVMs are relatively complex models intended to simulate the key processes that characterize the distribution of biomes or ecosystems and ecological responses to changes in climate or other forcing conditions at continental to global scales. Some studies have applied DVMs to the North American landmass, including recent comparisons of multiple models (e.g., Huntzinger et al. 2012) as well as more in-depth analyses with fewer models (e.g., Lenihan and Neilson 1995; Price and Scott 2006). These models generally project northward shifts of the major biomes in Canada, with an expansion of temperate forests in the east, a loss of boreal forest in the south, particularly in the western Prairie provinces, and a possible increase in deciduous content in B.C. interior forests. However, even these models do not normally capture the constraints on species colonization of new regions, so their results must be treated with some skepticism.

Additionally, much of Canada's boreal forest is underlain by permafrost (i.e., soils that are frozen continuously for periods of 2 years or more). Many recent studies have shown that since 1850, which marks the approximate end of the Little Ice Age in Canada, these boreal soils have warmed significantly (e.g., Smith et al. 2010). The warming has accelerated dramatically since the 1970s, causing permafrost degradation and melting and is evidently linked to global warming trends (Smith et al. 2010). Model projections (e.g., Zhang et al. 2008; Schaefer et al. 2011) now provide compelling evidence that permafrost loss is a pervasive and largely irreversible process affecting much of the northern Canadian boreal zone. The consequences are likely to include widespread losses of low-productivity ecosystems dominated by black spruce (which provide key habitat for woodland caribou), and increased areas affected by wildfires (notably after frozen peatlands melt and dry out to leave dead wood and dry peat). These processes are projected to lead to the release of major quantities of GHGs, which will contribute to a significant positive feedback effect on the global warming trend.

Social and Economic Scenarios

Scenarios of the social and economic consequences of climate change impacts on forests can be developed in several ways; however, the exact approach adopted will depend on the objectives of those developing and using the scenarios. The basic idea is to understand how changes in forest conditions brought about by climate change could affect forest-based social and economic systems. SFM scenarios can be developed that associate a particular scenario of climate change with future biophysical impacts on the forest and with the socioeconomic impacts that could occur under those conditions. This is not an easy task, but is an important area to pursue and discuss. The following section addresses how socioeconomic scenarios (SESs) and biophysical scenarios might be integrated.

Uses of Social and Economic Scenarios

SESs can be used to explore both the consequences and causes of environmental change at global, national, and smaller scales (Duinker and Grieg 2007). They are generally used in two ways: (1) to illustrate the possible trajectories of socioeconomic drivers of change and (2) to estimate the future socioeconomic impacts of climate change, as well as those resulting from other drivers, including adaptive capacity and vulnerability (Carter et al. 2001). In the first case, SESs explore the possible ways in which socioeconomic factors could evolve in the future, and these changes are then considered as socioeconomic drivers of environmental change.

The United Nations Development Program (Malone and La Rovere 2004) outlines five elements or categories that can be described in an SES. Demographic characteristics speak to the number of people living in an area and their distribution and also to the age, gender, health, education, and employment qualities of the population. Economic factors encompass aspects of market participation, public and private investment, income, savings, industrialization, infrastructure, labor, migration, and economic activity. Natural resource use refers to dependence on natural resources for economic, social, and cultural activities. Features that could be considered include the size of natural resource assets, the health or quality of these assets, their uses, the consequences of use, and the potential for future use given changes in management. Governance and policy refers to the priorities of governance, policy goals and mechanisms, planning and policy-making processes, the relevance and roles of different governance organizations and decision makers, and their effectiveness. Finally, culture addresses values and traditions concerning appropriate ways to achieve goals and address problems. For instance, social obligation, the relationship to and value of nature, trust in government and science, and lifestyle choices may be described. All of these elements could conceivably be important in an SES developed for an SFM system in Canada or elsewhere.

Scenarios of socioeconomic change can then be used to assess the influence of alternative socioeconomic trends on a future outcome of interest such as GHG emissions or land use. The IPCC has carried out four assessments of climate change since 1990 (see Appendix 2), of which three involved making projections of socioeconomic development and future GHG emissions. These projections were then distributed internationally to enable hundreds of researchers to assess their potential impacts on future climate. Each IPCC assessment used SESs that were based upon updated socioeconomic development and GHG emission trends. Analysis of these scenarios has revealed that similar emissions levels can result from different socioeconomic development pathways, and conversely, similar development pathways may produce very different levels of GHG emissions owing to uncertainties in both societal and ecological responses (Nakićenović et al. 2000).

In response to this realization, the IPCC's AR5 followed a new process of scenario development (Moss et al. 2010). The RCP scenario process began with the specification of different future GHG concentrations and then worked backwards in an effort to understand the patterns of socioeconomic development likely to cause the greatest contribution to GHG levels. The expectation is that this will help identify the most effective mitigation options (Inman 2011; also see Appendix 2).

van Drunen and Berkhout (2009) note that many SESs are based on similar assumptions about the relationships between development and environmental outcomes. However, such scenarios often differ in the sensitivity of environmental change ascribed to different socioeconomic drivers, producing differences in the projected timing, magnitude, and patterns of environmental change. In 2005, the Millennium Ecosystem Assessment (http://www.maweb.org/en/Scenarios.aspx) reviewed some of the major global scenario-building exercises that have been undertaken since 1995 (many of which are described in Appendix 1) and found that they often assumed common patterns of future development despite their diverse origins. Specifically, scenario worlds were found to develop gradually, influenced by several important driving forces, including either a strong policy push for sustainability, social fragmentation, environmental collapse, and institutional failure or the emergence of new human values and forms of development (Raskin et al. 2005). They reflected trends in global development such as rapid population growth, increasing production and consumption of goods and services, rapid technological development, increasingly decentralized authority, rising disparity between rich and poor, and increasing resource depletion and environmental degradation. Sometimes these scenarios depict the future as continuing business as usual, leading to futures with social and environmental breakdown, increasing natural resource scarcity, economic collapse, and environmental and social crises. Others describe the roles of the key actors (nations, governments, corporations, and consumers) and the functions of technology, values, policies, cooperation, markets, globalization, and other factors in achieving sustainable development.

Many socioeconomic scenarios also reflect common assumptions about relationships among different drivers of global environmental change. For instance, many scenarios are characterized by trade-offs between economic growth and environmental and social sustainability. Rounsevell and Metzger (2010), however, argue that such assumptions can polarize changes that are not necessarily mutually exclusive (i.e., it may be possible for both to occur at the same time). For example, they point to the IPCC SRES storylines that form the basis of many climate change scenarios (Fig. 3). By contrasting development that prioritizes economic growth with development that promotes environmental and social sustainability, some possible futures are excluded, for example, where free-market mechanisms are used to address environmental problems or where an environmentally conscious society supports strong economic growth. Hypotheses about these types of interrelationships are highly uncertain and very difficult to validate, but they are often taken as fact, which led Rounsevell and Metzger (2010) to assert that the underlying assumptions must be stated explicitly in storyline narratives. Doing so may help to rephrase analytical questions, for example, regarding the form or type of economic development that could contribute to a low-carbon future.

The second use of SESs, as described in subsequent sections, involves assessing the future socioeconomic impacts of climate change, including effects on adaptive capacity and vulnerability. This second use accounts for two important facts: (1) climate change will have both direct and indirect socioeconomic impacts and (2) these impacts will occur in a world that will have changed in other ways. For instance, the economic impacts of climate change on Canadian forests may also be affected by other drivers of economic change, such as increased public value placed on natural areas in an increasingly industrialized and populated world. To understand future socioeconomic conditions it becomes essential to consider these multiple drivers of change in an integrated way.

Kriegler et al. (2010) report that the use of global socioeconomic scenarios in climate change impact studies has been fairly limited to date. They suggest this to be the case because adaptation and vulnerability researchers have different research styles from those working on large-scale climate science, with the former often focused on smaller scale climatic changes and impacts. Kriegler and colleagues contend that there are often rather limited data available at the regional level as well as a lack of knowledge regarding modeling and scenario sensitivities and limitations, which can reduce confidence in model results. These authors also assert that adaptation and vulnerability research is highly sensitive to local conditions, with assessments being quite responsive to different scenario assumptions. For example, where global socioeconomic scenarios have been downscaled to model changes in population and economic growth at a regional scale, there is debate about the use of market exchange rates versus purchasing power parity as the common metric for economic data. The choice of this metric has the potential to result in substantially different outcomes from regional assessments of impacts and vulnerability (Carter et al. 2007).

Evaluating the Effects of Climate Change on Socioeconomic Outcomes

Socioeconomic impacts resulting from future biophysical and forest ecosystem changes can be evaluated using the same methods described previously (i.e., models, analogs, and through participation of stakeholders and (or) specialists). An important distinction exists, however, between market and nonmarket impacts resulting from climate change. Where ecosystems generate financial benefits, impacts can be estimated using monetary or market values. For example, where a scenario suggests that climate change could cause an increase in regional tree mortality as a result of prolonged drought in a specific forest-dependent region, the effects on timber supply and subsequently on employment, income, trade, and GDP could be evaluated and used to create a corresponding SFM scenario. Quantitative data for such economic activities may already exist and be readily available to support the use of economic models that simulate possible impacts under a set of changed conditions.

Many different types of economic models can be used to study the impacts of climate change. They include partial and general equilibrium models, input–output or Leontief models, and agent-based models, among others. Each type of model represents a specific kind of economic relationship or system and places importance on different economic features or variables that are central to its purpose. For example, computable general equilibrium (CGE) models are used to explore the dynamics of an interconnected system of economic sectors such as the global forest products market or a regional economy. CGE models are based on the premise that an economy is linked through economic transactions (purchases and sales) as well as competition for production inputs (labor, land, and capital; e.g., Williamson et al. 2008). Other alternatives, including risk models such as the Markowitz portfolio model, can be used to estimate the effects of climate change on economic conditions such as the minimum expected return for an investment portfolio made up of forest stands and stocks that could be harvested at different time periods (Williamson et al. 2011).

Model-based assessments can provide valuable information about the direction and magnitude of potential economic impacts of climate change by isolating impacts of climate change from other influences on socioeconomic conditions (Mendelsohn and Neumann 1999). For example, much of the research on timber market impacts has been conducted with models that simulate market activity with and without climate change, holding other factors such as demand and prices constant (Osman-Elasha et al. 2009). According to Osman-Elasha et al. (2009), the effects of three distinct forest impacts have been studied extensively using economic models, namely changes in timber yield; changes in natural disturbance regimes; and the shifting of species and ecosystem types. The effects of these changes are typically modeled using AAC or maximum sustainable yield as a constraint on some forest sector metric of economic well-being, such as sector competitiveness, international trade of forest products, employment income, government tax revenues, etc. (Hauer et al. 2001). Potential impacts of climate change are then estimated using economic models that simulate future outcomes, either by altering production inputs to reflect projected changes in forest conditions or by examining a range of input values to determine economic sensitivity to changing conditions (Alig 2010). Regional studies in Canada and the United States have shown that production output and sector profitability are highly sensitive to the effects of climate change on timber supply, particularly as climate change affects forest disturbances and productivity in other countries (Osman-Elasha et al. 2009). More specifically, climate change is projected to increase global forest productivity and timber supply overall, although some regions, including North America, are expected to experience negative market outcomes (see review by Williamson and Johnston 2009). Reductions in competitiveness are anticipated owing to higher labor costs in North America and generally improved growing conditions in many tropical countries.

Additionally, models are often used to determine the possible effectiveness of different responses in mediating economic impacts. For instance, Irland et al. (2001) compared multiple analyses of the economic impacts of climate change on US timber and wood-product markets, finding that adaptations such as salvage logging or regeneration using new species offset a great deal of the negative economic effects of climate change and could even support increased consumer and producer welfare in some cases. However, it must be noted that many economic models reflect neoclassical assumptions about economic behavior such as cost minimization and consumption optimization, which may not accurately reflect adaptive behavior in Canadian SFM. For instance, most studies of climate impacts on timber supply do not consider land ownership patterns in Canada (Alig 2010). Because most forest land in Canada is publically owned and timber supply is often determined administratively rather than by markets, it can be difficult to model adjustments in timber supply as the result of simple economic processes (Hauer et al. 2001). Similarly, the use of assumptions from rational choice theory may not reflect decision making that is more strongly influenced by cultural ties to regional industries or other irrational factors that affect consumer behavior not commonly captured in economic models.

Most of the studies examining climate impacts on timber supply also do not account for nonclimatic drivers such as land use change. Instead, many have assumed that the total area of forested land will remain unchanged while the climate changes, although conversion of forest land to agriculture, for example, may be a crucial adaptation process to overcome global food shortages, with major implications for forest-based economies. Impact assessments undertaken from a forest sector perspective should therefore consider climate change responses in agriculture and other potentially competing land uses (Hauer et al. 2001). Similarly, mitigation policies that seek to reduce deforestation or increase afforestation to facilitate increased carbon sequestration (see http://www.for.gov.bc.ca/hfp/znd/index.htm) could also alter land use, with substantial implications for the forest sector. In this case, carbon storage in standing forests as well as wood products, carbon pricing, and belowground carbon stocks may become important considerations in determining the total value of the forest and could lead to major changes in management strategies away from those of traditional forestry (Hauer et al. 2001).

Forest ecosystems are also associated with important nonmarket values that will be affected by climate change. Of the assessments that have looked at the economic impacts of climate change, relatively few explore the effects on nontimber goods and services (NRTEE 2011). Nontimber forest products, including food, fuel, and medicines, are important to the livelihoods and socioeconomic well-being of many Canadians, particularly in rural areas. However, data on the collection and sale of nontimber products is often limited, making impact assessments difficult. Research on these types of impacts requires greater attention (Easterling et al. 2007), particularly for forest-based communities with subsistence lifestyles (Eastaugh 2008).

Climate change impacts on recreation and tourism have received more attention than impacts on many other nontimber goods and services. Studies have examined the effects of climate change on visits to national parks and participation in activities such as skiing, fishing, and hunting. Overall this research indicates that winter activities could be negatively affected, while summertime activities would benefit from a longer season (e.g., Mendelsohn and Markowski 1999). However, impacts are difficult to assess because there are limited benchmarks against which to measure the impacts of climate change; there is high uncertainty about local- and regional-scale changes in climate and ecological responses; and over time people tend to adapt their recreation to circumvent negative impacts (Hauer et al. 2001). For example, Scott et al. (2008) found that many estimates of potential climate change impacts on the ski industry did not consider adaptation by operators (e.g., snowmaking) or by skiers (e.g., reduced activity or change of location). These authors estimate, for instance, that large investment in snowmaking by ski hill operations in the northeast United States could substantially reduce negative impacts on the industry, leaving it financially viable long into the future. Similarly, relocation of snowmobiling to locations with adequate natural snow may be of benefit to winter recreation destinations that market their areas to snowmobilers in other areas.

Climate change could also affect sociocultural values such as the aesthetic qualities of forest landscapes as well as existence values (the knowledge that a species or habitat exists), bequest values (ensuring that a natural resource is shared with future generations), and option values (having the ability to use a resource in the future) (Hauer et al. 2001). Many of these values are derived from social and cultural attachment to place (the psychological connections with specific forest landscapes or regions). Forest landscapes can have deep symbolic meanings that influence and affect culture as well as the institutions that guide human interaction with the environment (Young and Lipton 2006). For instance, Stedman (1999) argues that the identity of forest-dependent communities as timber towns, where logging and forestry are a way of life, has played a significant role in the conceptualization of forest ecosystems and has contributed to the current paradigm of sustainable forest management.

Climate change could thus affect how people define themselves and the world around them, as well as the ways in which they interact with the environment (Adger et al. 2009). Forested places that are culturally or spiritually important to people may be changed or lost, with profound impacts on the cultures established around specific forestry-related resources, activities, customs, or livelihoods. Additionally, climate change in forest-based regions could influence social stress and pathologies such as crime, alcoholism, and drug abuse, exacerbating social dysfunction and conflict (Hauer et al. 2001). Moreover, climate change may have substantial implications for health, leisure, recreation, and cultural and traditional activities associated with forests that contribute to social well-being (Hauer et al. 2001). For instance, an increased frequency and intensity of forest fires could have negative effects on human health, including increased risk of respiratory disorders (see Adger et al. 2009).

Evaluating the impacts of climate change on nonmarket values is often difficult, because the economic metrics most commonly used to estimate climate impacts typically do not or cannot account for nonmarket values. As a result, socioeconomic impacts are likely to be underestimated and even excluded from adaptive and mitigative decision making (Adger et al. 2009). The monetization of ecosystem services is an area of research that is rapidly expanding and may help to address gaps in model-based estimates of impacts. Techniques such as "revealed and stated preferences" examine people's choices to infer an economic value and are increasingly being used to estimate the nonmarket value of ecosystems and could play an increasing role in estimating impacts of climate change. However, work is needed to address the full range of nonmarket benefits that accrue from forests in different locations. Data on nonmarket forest values can be obtained using surveys or price experiments, but these methods can be costly and labor intensive. Some also use economic concepts that may not capture all types of forest values. Snyder et al. (2003), for example, argue that many economic valuation methods rely on Western systems of valuation that are incompatible with indigenous perspectives on landscape value and do not capture cultural attachment to place. Of course, this argument applies equally to nonindigenous cultures: many North Americans value forests as natural places far more highly than as mere sources of raw materials for house construction and paper products. Therefore, economic valuation is often insufficient to calculate the social and cultural loss that would be experienced by individuals and communities in rural and forested locations.

New methods such as landscape values mapping may be able to capture possible climate change impacts on nonuse values (Novaczek et al. 2011). Developed by Brown (2005) (see also Brown and Reed 2000, 2009), this technique attempts to link information on qualitative values systematically with spatial data to support geospatial analysis for natural resource management. Stakeholders, including local specialists, interest groups, government agencies, and individual community members, are engaged in the mapping process and asked to place symbols representing different types of landscape values on a map. This makes the range of values associated with a specific place visible and allows for the identification of places that are culturally important — termed "values hotspots" by Beverly et al. (2008) — so that they can be considered in adaptation planning (Novaczek et al. 2011).

To date, few studies have quantified nonmarket social and economic costs of climate change impacts on forest ecosystem services. National-level assessments, for instance, have predominantly discussed these types of impacts qualitatively (NRTEE 2011). Therefore, this dimension of socioeconomic impacts is often evaluated using expert or stakeholder input and described qualitatively in impact scenarios. Quantitative impacts assessments are also limited in their ability to account for surprise events or structural changes in social or economic systems; hence they can provide only a partial picture of possible climate impacts. Learning from recent or past events in other regions (using space as an analog for time) may be a better means of developing management interventions, or responses to surprise events and structural changes, and may therefore be an acceptable alternative or complement to modeling approaches. For instance, exploring past experiences in other areas where changes in the forest occurred (due to historical climatic events and (or) variability, or other changes) can be used to prepare management strategies in anticipation of future change. This would influence the future flow of forest-based goods and services, to the long-term benefit of the individuals or groups that depend on them (Turner et al. 2003). Additionally, this exploration may be useful to elicit researcher or stakeholder opinions on potential socioeconomic impacts.

Assessing Future Socioeconomic Impacts of Climate Change

The socioeconomic consequences of climate change cannot be considered in isolation because they will occur in parallel with the effects of nonclimatic drivers, such as economic growth, demographic change, technological change, changes in governance, and changes in lifestyle (Berkhout and van Drunen 2007). Hence, analyses often attempt to identify the key nonclimatic drivers of present-day socioeconomic conditions and then assess potential changes in these drivers and the consequences for future socioeconomic outcomes. For instance, Adger et al. (2009; IUFRO report) list energy demand, agricultural markets, governance, economic growth and exchange rates as key nonclimatic drivers of global wood supply and demand. Nationally, Duinker (2008) identified some important nonclimatic drivers of change in the Canadian forest sector, including global demand for forest products and Canadian wood supply, invasive species, geopolitics, global energy, technology, governance, aboriginal empowerment, air pollution, conflict over resources, society's forest values, demographics, and industry profitability. These nonclimatic drivers will have important implications for the future social and economic impacts of climate change.

Projections of future socioeconomic trends are normally captured in socioeconomic scenarios such as those described in Appendix 1. These scenarios can be used to understand both the factors driving climatic and forest change and to project the future socioeconomic context that will be affected by climate change. Feenstra et al. (1998) suggest that SES can be used to perturb nonclimatic influences on a socioeconomic system of interest and add these to the biophysical impacts of climate change. However, such an approach has limitations (see Fig. 7).

The socioeconomic scenarios used to project impacts of climate change can be based upon two different sources of information: downscaled global socioeconomic development scenarios or independent local socioeconomic data. To date, the use of downscaled global socioeconomic development scenarios has been limited, because downscaling is often restricted to national or larger regions and focused only on changes in GDP and population (Kriegler et al. 2010). Such data are often not useful for sectoral economic projections, which can have greater local importance and may be highly sensitive to different scenario assumptions.

Alternatively, impact assessments can use smaller scale sources of information such as national and regional forecasts of social and economic change (CCIAD 2007). The challenge with this approach is that these forecasts normally consider a much shorter timeline (less than 30 years) than those used to assess the impacts of climate change (normally to 2100), and they are not normally linked to global scenarios (Kriegler et al. 2010). The US National Research Council's Committee on the Human Dimensions of Global Change and the Climate Research Committee (Moss et al. 2010) note that the development of local socioeconomic scenarios with different degrees of coupling to global GHG emissions will be particularly important for future vulnerability and adaptation research at local scales.

Regardless of which sources of information are used, it is important that the assumptions used to project local socioeconomic trends be consistent with those used to project GHG levels and climate change (Feenstra et al. 1998). Berkhout and van Drunen (2007) also reiterate that multiple scenarios of future socioeconomic development should be used to avoid reliance on a single picture of the future — which would otherwise narrow the representation of possible outcomes and hide key sources of uncertainty. Two of these case studies adopted socioeconomic scenarios consistent with the IPCC SRES and the consequent climate projections, to assess a range of socioeconomic impacts.

Choosing a Discount Rate

An important issue in estimating the socioeconomic impacts of alternative climate change scenarios relates to the discount rate used to value future benefits and costs (Cohen and Waddell 2009). Discounting reflects the idea that most people would rather consume

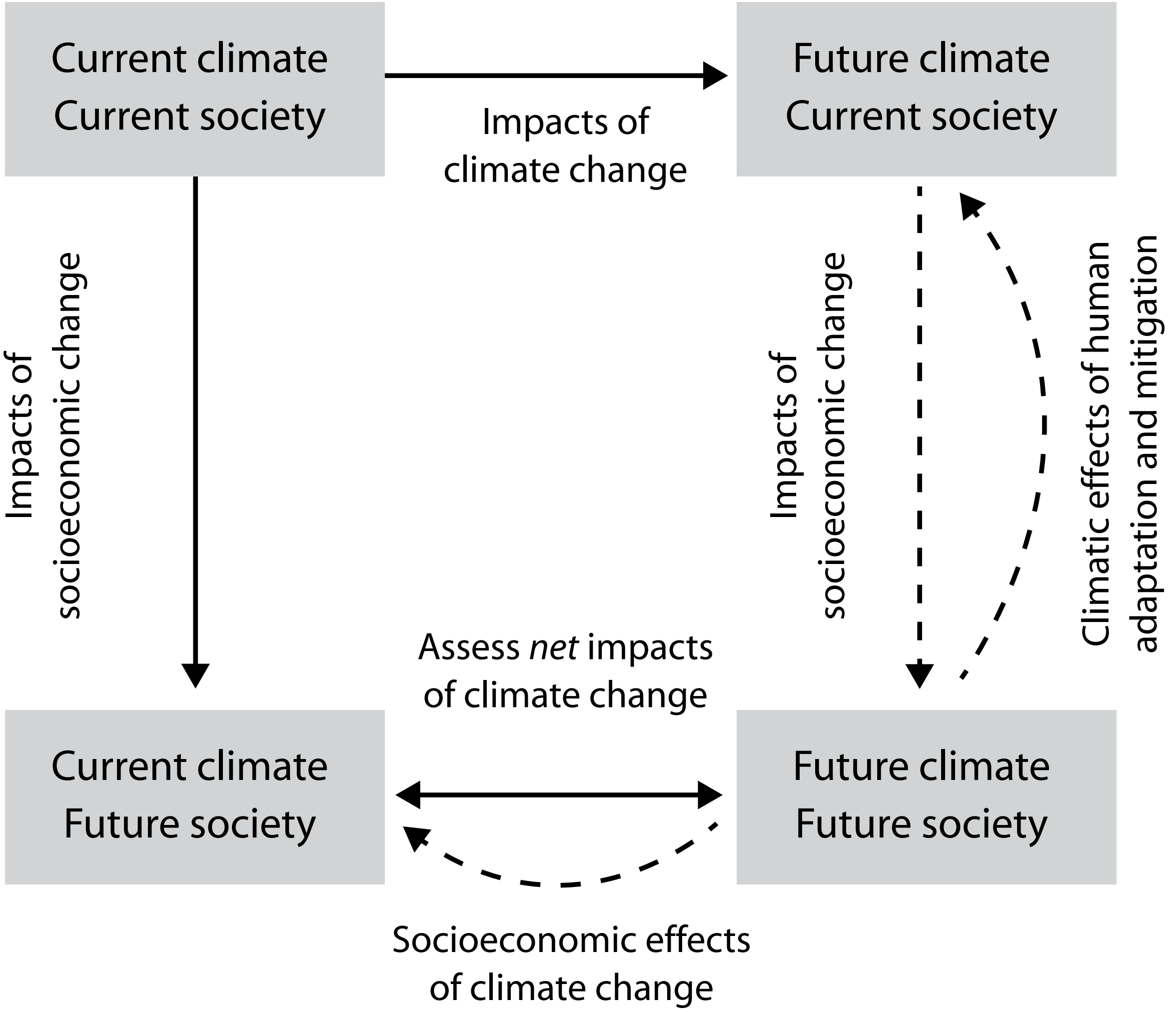

Figure 7. Conceptual use of socioeconomic and climate change scenarios to assess the impacts of global change on a coupled biophysical and socioeconomic system (such as a sustainable forest management system). The current state of the system can be analyzed with both climate and society in their present state (top left). The future impacts of societal changes are projected using a socioeconomic driving scenario (bottom left). The same global socioeconomic drivers are used to project future greenhouse emissions, future climate, and impacts on the biophysical system (i.e., the forest) — this represents the impact that climate change will have on today's SFM system (top right). In reality, however, both climatic and socioeconomic changes occur concurrently (bottom right), so a method is required to assess future societal impacts of the future biophysical system (and future biophysical impacts of the future society). In practice, this is likely to be done by adding the projected societal changes to the projected biophysical conditions (indicated by the vertical dashed arrow from top right to bottom right). Then the net impacts of climate change to society can be assessed by comparing the bottom-left and bottom-right projections. This scheme does not account for environmental and societal feedbacks, which may mitigate or exacerbate the first-order impacts of climate change on the future SFM system (indicated by curved dashed arrows). Adapted from Feenstra et al. (1998).

goods and services today than in the future (Hauer et al. 2001). In the context of climate change, discounting is useful for understanding how economic costs and benefits occurring in the future (including those accruing from present-day actions) can be assigned present-day values to choose the most cost-effective adaptation pathway. The technique involves estimating a future impact and then applying a discount rate (percent per year) that reflects social preferences for trade-offs between current and future consumption and hence estimates the current value of future costs or benefits. These discounted values, often reported as the "net present value", facilitate comparisons between impacts occurring at different points in time under different scenarios of socioeconomic development and climate change. Thus, discounting provides a way to compare investments proposed today to adapt to, or mitigate, the impacts that would occur in the future, and could include assessing the costs of future damage if nothing is done (the cost of inaction). Such comparisons can provide an economic basis to support decision making about appropriate adaptive actions (Hauer et al. 2001).

While discounting is widely accepted as a practical means of describing human economic behavior, there is little consensus about the appropriate discount rate that should be used for comparing climate-change adaptation strategies (Hauer et al. 2001). Discounting may provide a valid standard for analyzing public policies, but its underlying assumptions are increasingly being challenged on the grounds of intergenerational ethics and the distribution of impacts through time and space (Frederick et al. 2002). For instance, Ng (2011) argues that using a higher discount rate (i.e., putting greater preference on current well-being) reduces the perceived need for strong environmental protection until far into the future. He also notes that this framework does not account for extreme disasters, whose avoidance may justify the use of stronger actions now. Thus there are ethical arguments for using lower discount rates when making decisions about public investment in adaptation and mitigation. The choice of discount rate has a substantial influence on the calculation of damages associated with future climate change impacts as well as the avoided damages gained through adaptation investments (see Cohen and Waddell 2009). Hauer et al. (2001) suggest that sensitivity analysis (using a range of different discount rates) can highlight these important intergenerational distribution and equity issues for decision makers.

Exploring Feedback between Socioeconomic Development and Climate Change Impacts

Many assessments of economic impacts assume a linear path from climate to ecological systems to social systems (see Fig. 6), but this approach is overly simplistic because it does not capture management feedbacks that can affect ecosystem sensitivity and (or) exposure. For example, Sohngen et al. (1998) suggest that management reactions to climate change are likely to reduce exposure or sensitivity, so linear assessments are likely to overestimate the impacts. In Canada, this linear approach may be useful for estimating socioeconomic impacts occurring in forested areas that are not actively managed. But for managed forests, such as those used for timber production and for parks and other protected areas, the impacts of climate change on forests are likely to be at least partially mitigated through management actions.

On the other hand, while it is clear that a coevolutionary approach that captures interactions between climate change and socioeconomic development is more realistic, there are potential pitfalls in the circular reasoning (Lorenzoni et al. 2000). Shackley and Deanwood (2003) identify four reasons why using independent scenarios may be better for impacts assessment: (1) interactive scenarios amplify complexity and uncertainty, which can hinder stakeholder engagement; (2) independent treatment of climatic and socioeconomic futures reveals the extreme case of no response to climate change (i.e., a worst-case scenario that may be helpful for policy development); (3) independent scenarios also provide a clearer distinction among the effects of different causes of change; and (4) the integration process becomes less viable when mitigation and adaptation feedbacks are taken into account.

In practice, both the linear and co-evolutionary approaches may be useful in an assessment exercise. For instance, a linear approach could be used to highlight the effects of different drivers of change and to demonstrate a range of worst-case, no-action scenarios that could then be compared with projections of impacts that assume particular types and (or) levels of adaptation.

Using Sustainable Forest Management Scenarios for Vulnerability Assessment

Williamson et al. (2012) provide a vulnerability and adaptation assessment framework that is applicable to SFM in Canada. Its purpose is to enable forest managers to determine how SFM may be vulnerable to climate change and then develop appropriate management strategies to minimize the impacts (and maximize any benefits) in the region of interest. The assessment approach (see Fig. 2 of Williamson et al. 2012) comprises six integrated components:

(1) Provide context

(2) Describe current climate and forest condition

(3) Develop scenarios of future climate and forest condition

(4) Assess vulnerability of SFM to current and future climate

(5) Develop and refine adaptation options

(6) Implement and mainstream adaptation

The following text provides an overview of the steps involved in component 4 (i.e., applying the scenarios), in combination with determinations of system sensitivity and adaptive capacity, to determine future vulnerability of SFM. Following the approach outlined in Williamson et al. (2012), there are three distinct steps in determining future vulnerability:

- Assess future exposure (i.e., to changes in climate)
- Infer sensitivity to change (requiring knowledge of system function)
- Assess adaptive capacity

Assessment of future exposure to climate change requires access to climate scenarios for the region of interest and a process to evaluate their potential impacts. Sensitivity (responsiveness) of the forest management system to the different scenarios will then need to be determined in some way. The vulnerability framework of Williamson et al. (2012), ecological models, and the CCFM suite of Criteria and Indicators (C&I) for SFM are proposed as possible approaches for assessing sensitivity, though other methods might be more appropriate, depending on the region concerned and the questions being posed. Vulnerability assessment also requires consideration of the adaptive capacity within the system of interest (also see Williamson and Isaac 2013), which focuses on the human resources available for adaptation, but may include the natural resilience of the forest ecosystems being managed.

Downscaling Climate Scenarios

As stated previously, it is highly desirable to carry out these assessments using multiple contrasting scenarios (i.e., generated by different climate models and (or) forced by different GHG emissions scenarios). In general, climate scenarios will need some form of downscaling from the global or continental scale to be useful for the assessment of local exposure.

Results from multiple GCMs are desirable because even though these models represent current scientific knowledge of how the global climate system is likely to respond to changes in GHG concentrations, they are imperfect. Hence, no GCM projection should be interpreted as a precise forecast of future climate. Vulnerability assessments should be based on a suite of these projections as a way of better accounting for the range of possibilities and to attach estimates of uncertainty. This suite of projections will need to be downscaled to the relevant area of interest.

A key problem in the downscaling process is that many investigators, including scientists and strategic planners, lack the time and expertise needed to extract and manipulate data from huge global data sets for application to smaller regions. There are various approaches for doing this, which include software tools that can be used online or are available as downloadable packages. Several organizations have also created downscaled data sets that are freely available (see also Appendix 2). Figure 8 shows the example of downscaling GCM data using an RCM to apply them at local scales. Barrow and coworkers of the Canadian Climate Impacts Scenarios (CCIS) group of Environment Canada (since superseded by the Pacific Climate Impacts Consortium, PCIC), have provided guidance on selecting and interpreting GCM projections and applying them at regional to local scales within Canada, as well as developing data sets and techniques for impacts researchers to use (e.g., Wilby et al. 2002; Lines and Barrow 2004; Barrow and Yu 2005).

The general approaches to downscaling GCM results can be grouped into four categories, each with advantages and disadvantages, but with some common features. In essence, climate model projections may be biased, so they need to be referenced to some historical baseline period that can be compared with observed data. The modeled change in climate between the baseline and the simulated future climate then becomes "the warming signal", which can be combined with the observed data in some way. Hence

Current climate + climate change
scenario ⟶ Future climate scenario

Starting with the simplest, these approaches are as follows.

Use Changes Projected for the Nearest General Circulation Model Grid Point

Advantages: This approach is the simplest method. Disadvantages: GCM grids are typically very large and hence a lot of the potential topographic influences on climate and climatic trends are lost. This is becoming less of a problem, however, because GCM grid resolutions have increased greatly in the past 10 years (e.g., see IPCC 2014). It is inadvisable to use estimates of changes from a single grid node because these may be atypical. Recommendations are to average the change values from four or even nine neighboring grid nodes.

Interpolate among General Circulation Model Grid Nodes Using a Numerical Approach

Interpolation techniques such as inverse distance weighting, kriging, or surface splines can be used to estimate the climate at specific locations (or at points on a finer scale grid).

Advantages: Interpolation techniques provide a more precise estimate for specific locations, accounting for the influences of values at multiple grid nodes. Interpolated estimates of changes should generally be combined with data from local climate stations, interpolated to the same locations to provide more plausible estimates of future climate and how it will vary spatially. Many interpolated data sets are now available, for areas ranging from single provinces to the continental scale (see Appendix 2). Disadvantages: Interpolation requires access to significant computing resources and expertise; interpolating to high spatial resolution may suggest more precision in estimates of future climate than is justified given the limitations in GCM projections (though similar arguments apply to other methods such as statistical and dynamical downscaling).

Use Statistical Downscaling

Statistical downscaling covers a range of methods that seek to build statistical relationships between observable meteorological phenomena (as captured, for example, in global reanalysis data) and mechanistic simulations of the same meteorology by the climate model. These relationships are then applied to future simulated meteorology, leading to a more mechanistic prediction of the local climate than can be achieved by simple spatial interpolation. Advantages: Statistical downscaling is a more mechanistic approach than interpolation. Disadvantages: Statistical downscaling is complicated, requiring sophisticated software such as SDSM (Statistical DownScaling Model; e.g., Wilby et al. 2002; see also http://www.cics.uvic.ca/scenarios/index.cgi?More_Info-Downscaling_Tools).

Use Dynamical Downscaling

Dynamical downscaling is a more process-oriented approach typically performed using RCMs, which are similar in design to GCMs, but are instead designed to operate over smaller areas (such as a subcontinent) at a finer grid resolution (Figs. 5 and 8). In general, they are organized on a three-dimensional grid box nested within a GCM (or within the data set generated by a GCM), so that the boundary conditions (at the sides of the box) are prescribed externally. Advantages: Dynamical downscaling provides a simulation of future

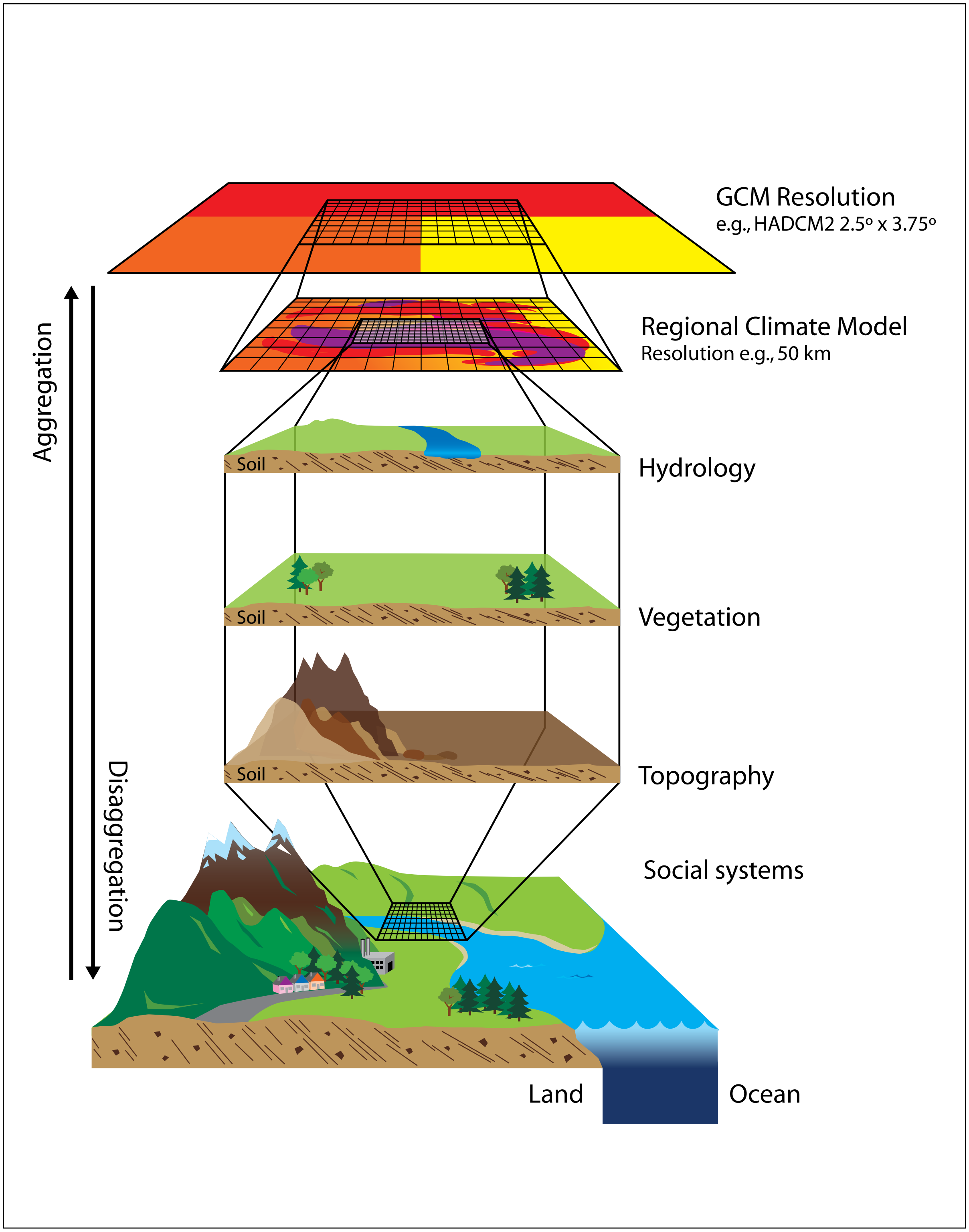

Figure 8. The concept of downscaling: many processes that control local climate and weather, including topography, vegetation cover, and the proximity of lakes and rivers, are not captured in global-scale climate models, but are needed to focus the projected changes onto a small region of interest. The approach shown here is to use a regional climate model, but other less sophisticated approaches are possible. Image obtained from David Viner, Climatic Research Unit, University of East Anglia and used with permission. GCM = general circulation model.

meteorology (i.e., on daily time scales) and long-term climate that is entirely defined by the forcing GCM and internally consistent; the projected climate is comparable to that produced by statistical downscaling but extends over a larger area. Disadvantages: RCMs are computationally very difficult and expensive to operate (comparable to running a fully coupled GCM) and require access to GCM output. Many RCMs are calibrated to run for a particular region (e.g., the Canadian RCM is restricted to Canada and the United States, so comparison of different models applied to the same region is very difficult to organize); simulations are restricted to those already carried out with the hosting GCM, and for practical reasons are often limited to relatively short periods of 10 or 15 years. (The latest results of the North American Regional Climate Change Assessment Program, NARCCAP, https://www.narccap.ucar.edu/results.html, demonstrate the capabilities of current generations RCMs). An interesting tool intended to generate high-resolution scenarios from RCM output exists called PRECIS (http://www.adaptationlearning.net/guidance-tools/workbook-generating-high-resolution-climate-change-scenarios-using-precis), with a workbook published in 2003.

Assessing Future Exposure to Climate Change

In simple terms, downscaled climate scenarios are projections of future exposure to climate, but the possible impacts generally need some form of interpretation. Snover et al. (2007) provided an outline of the questions one might ask when studying climate scenarios (shown here in a modified form in Table 2), though not all of these questions will be answered by the data sets available (Appendix 2). Important questions relate to how much the mean conditions are projected to change, but

Table 2. Questions to determine trends, extremes, and inter-annual and intra-annual variability from climate change scenario data, modified from Snover et al. (2007)

Question	Examples
What are the projected extremes in the future?	• What are projected highest and lowest temperatures during winter and summer over a future period of 10 years or more? • What are projected largest and smallest precipitation amounts, for single months and for single events? • Are these extremes larger or smaller than past extremes of temperature and rainfall?
What is the projected periodicity of extreme events (e.g., droughts, floods, heat waves) in the future?	• Does the frequency of extreme events increase or decrease during the 21st century (or longer period)?
What is the apparent overall trend in inter-annual variability going forward into the future?	• Does variability generally increase, decrease, or remain relatively unchanged during the 21st century (or longer period)? • Are the projected changes larger or smaller than variations between cold and warm, or wet and dry, years in the past? • If change is evident, does the rate of change increase over time?
How is intra-annual variation of temperature and precipitation and other factors projected to change into the future?	• What is the difference between summer and winter temperatures, and between largest and smallest precipitation amounts, during a single year? • How does this difference change over several decades? • How do these differences compare with past data?
Are there episodes in the historical record that resemble conditions or events projected for the future?	• These kinds of "natural experiments" are useful to assess possible impacts and societal responses of similar but more frequent and (or) more intense episodes in the future.

for many situations, changes in the extremes may be more critical. As was discussed earlier, GCM projections of changes in variability and extremes cannot be considered reliable, though some investigations suggest there is useful information that can be extracted (e.g., Kharin and Zwiers 2005). In practice, determining whether changes in variability projected by GCMs are statistically meaningful requires particular expertise: groups conducting a vulnerability assessment may approach an expert climate scientist to help locate and interpret current information on projections of climate variability and extremes for the region of interest.

In most cases, it is probably simplest to assume that the variability observable in past climate records will persist in the future, even as the means may increase or decrease. Note that superimposing observed variability on a trend of increasing mean temperature, for example, will cause the distribution of temperatures exceeding a specified extreme temperature to shift upwards. Hence, the first order effect of warming on temperature extremes will be captured. Additional scenarios can be developed, for example, by applying a factor to the monthly anomalies that increases or decreases each year into the future — possibly based on recent observed trends. This could be used to explore systematic changes in the variability of one or more key variables (such as precipitation), where plausible changes would be cause for concern.

Assessing Sensitivity of Sustainable Forest Management to Climate Change

As discussed previously, ecological and socioeconomic responses to climate change can be assessed using several approaches, including observations (e.g., using spatial differences as analogs for changes over time) and climate-sensitive models (of both ecosystems and socioeconomic systems). However, the sensitivity of an SFM system to climate change will be a complex outcome resulting from the integrated responses of many individual elements of the system (both biological and human) to changes in several climatic drivers. Hence, what appears to be needed is a holistic suite of the key ecological and socioeconomic indicators of SFM responsiveness to climate, which can be monitored over time and projected into the future using multiple models.

One approach might be to modify the existing national system of science-based C&I for SFM in Canada as developed for CCFM (CCFM 2006). The C&I framework has become a key component of Canadian SFM, providing a basis for measuring progress in achieving and maintaining sustainability, and for certification of SFM when competing in foreign markets for wood products. However, the current system (six criteria and 46 indicators) does not account for the potential impacts of climate change. Hence, Steenberg et al. (2013) have provided a review and recommendations for how existing indicators may need to be modified or where additional indicators are required. It should be noted that C&I are not the only definitions or measures of SFM used in Canada, so the following discussion of possible application to climate change impacts should be regarded as an example; actual impact assessment projects may choose to adopt other methods.

Five of the six criteria used to define and measure SFM in Canada address its role in maintaining: (1) biological diversity; (2) ecosystem condition and productivity; (3) soil and water properties; (4) global ecological cycles (particularly the carbon cycle); and (5) the economic and social benefits of forests. Criterion 6, society’s responsibility, addresses the importance of SFM as a participatory process that benefits all Canadians (CCFM 2008).

Criteria 1–4 refer to specific biophysical features of forests. Of particular importance, forest growth, competition, and mortality are distinct climate-sensitive elements of stand development and succession captured by criterion 2. Many natural disturbance agents (e.g., wildfires, insect attacks) are also strongly affected by climatic factors and are key ecosystem processes that can cause major changes in the proportions of living biomass and dead organic material in forests, and hence play a crucial role in the forest carbon cycle (captured by criterion 4). Conversely, criteria 5 and 6 are related to the provision and maintenance of social and economic benefits that come from forests managed with long-term sustainability objectives.

Given that climate change is expected to affect forest ecosystems, the C&I framework provides a scientific basis for assessing the sensitivity of SFM to changes in climate. Assuming that the effects can be quantified, then these indicators can also provide a measure of responsiveness. (It is important to distinguish the term sensitivity as it is used in vulnerability analysis (as an integral component of potential impacts on the SFM system) from its use in C&I terminology. Following Steenberg et al. (2013), we use "responsiveness" here to describe how an indicator responds to changes in management practices.) The total change in multiple indicators could therefore be used as a means of assessing the sensitivity of the entire SFM system to climate and hence to quantify potential impacts of changes for different scenarios (i.e., exposures) of future climate. However, as Steenberg et al. (2013) note, biophysical indicators are far more easily measured than social and economic indicators, implying that other approaches may be needed for determining sensitivities of social systems. Steenberg et al. (2013) also distinguished action indicators, which track quality and quantity of management actions, from state indicators, which report on how the system has responded to management and external factors (including climate change). In general, they found that the state indicators became less reliable with climate change impacts, whereas many action indicators increased in value because they can track the effectiveness of management actions aimed at adaptation or mitigation.

For example, C&I indicator 2.5 is an action indicator that tracks the proportion of harvested areas that are successfully regenerated. Clearly, with no management interventions, climate change is likely to reduce natural regeneration success in most situations (though not all), because the new conditions will become increasingly different from those that allowed the parent trees to establish and grow to maturity. However, with appropriate silvicultural prescriptions, including the possibility of planting new, better-adapted species or genotypes, the area regenerated successfully will increase. The net change in regenerated area therefore becomes an indicator of the sensitivity of SFM to the change in climate (though it may be limited by human adaptive capacity to implement the necessary prescriptions on a large enough scale). It may also be advantageous to implement adaptive management practices sooner rather than later, to learn as much as possible about this sensitivity in the early stages of climate change. Then, in principle, this information can be combined with projections of future climate (i.e., of exposure) to assess the likely future impacts on regeneration success and on the amount of investment in silviculture required to maintain or enhance it.

There remains a wide gap between the research on the conceptual relationships of climate change exposure and sensitivity and the practical application of these principles to vulnerability assessment. The use of C&I applied to SFM may be a practical means of bridging some of that gap.

Evaluating the Adaptive Capacity of Sustainable Forest Management

Adaptive capacity refers to the ability of a system (human or biological) to cope with, adapt to, and recover from the impacts of climate change (Smith et al. 2001). It is important to consider adaptive capacity when determining vulnerability, because adaptation can mitigate some of the potential impacts of climate change. Adaptive capacity also pertains to the state of a system before disturbance and refers to its potential to adjust to the impacts by reducing or eliminating the negative impacts and capitalizing on the opportunities presented (e.g., Smith et al. 2001).

The concept of adaptive capacity applies to both ecological and human systems. For ecosystems, adaptive capacity derives from diversity — in genotypes, species composition, and landscape structure — which drives adjustments in response to variations in climate and other environmental factors (e.g., Peterson et al. 1998; Carpenter et al. 2001; Bengtsson et al. 2003; Folke et al. 2003). Here, however, the focus is on the human dimensions of SFM. Forest management activities can intervene to reduce the effects of climate change on forests through activities such as planting resilient tree species, "fire-smarting" forest landscapes, assisted tree migration, etc. SFM may also mitigate the social and economic impacts of climate change by reducing dependence on vulnerable forest ecosystems or species or by seizing opportunities for new benefits arising from the establishment of new species or ecosystem types. Therefore, the capacity of forest management to both mitigate the negative impacts of climate change on forests and sustain the human systems that depend on them, as well as to take advantage of new forest-based benefits arising from climate change, are all elements of adaptive capacity.

Williamson and Isaac (2013) review the relevance of adaptive capacity to SFM and how adaptive capacity can be understood, assessed, and managed within SFM. Current adaptive capacity can be described by listing assets that are or could be used for adaptation (sometimes called the determinants of adaptive capacity). These include human and natural capital, social networks, information, economic and financial resources, built infrastructure, cultural and institutional capital, and many others. The description can be very general, however, so it may be helpful to focus on the assets that are relevant to current climate exposure and describe their flexibility, liquidity, substitutability, or other characteristics. It may also be helpful to examine past experiences with climatic extremes and variability or to use spatial analogs, to understand the capacity required to deal with climate impacts, and to assess the processes or types of adaptation need to adjust SFM to these impacts. A description of the precise aspects of SFM that could be adjusted to better cope with current climate (e.g., changes in planning processes, management policies, or planting practices) may also help to highlight existing deficiencies in capacity or barriers that could inhibit future adaptation.

Assessing Vulnerability of Sustainable Forest Management

The process of linking projections of future changes in climate and forest conditions to the determination of SFM vulnerability requires both anticipation of impacts (positive or negative) and consideration of the potential mitigation of those impacts implied by the adaptive capacity available. Clearly, the vulnerability of a system is region and time specific, so any attempt to assess vulnerability must occur at appropriate spatial and temporal scales. For example, Metzger et al. (2005) explored the sensitivity of key ecosystem services to the combined effects of climate change and other global and regional stressors — including social and economic factors — using the spatially explicit ATEAM approach. This approach integrated a range of model projections based on internally consistent sets of scenarios and produced results that could be displayed as continental-scale vulnerability maps, allowing comparisons among ecosystem services and socioeconomic sectors, for the different forcing scenarios.

Ideally, the sensitivity of SFM to climate change should be determined for as many as possible of the goods and services that the forest provides. As suggested previously, a comprehensive approach might involve tracking or projecting changes in appropriate indicators of SFM, for example, from the CCFM’s national (or local level) suite of C&I. In practice, assessments that consider multiple aspects of SFM can be complex, expensive, and time consuming. Hence, in some cases, the assessment may focus on some key aspect of the system of particular importance. For example, sensitivity of the forest sector could be represented simply by estimating the impacts on wood supply, as was done by Williamson et al. (2008) for Vanderhoof, B.C.

As previously noted, adaptive capacity should also be considered as part of a vulnerability assessment. This could involve comparing the current capacity to address present-day climate variability and extremes with what would be required in future, to cope with and adapt to, the projected effects of climate change (Williamson and Isaac 2013). If it is determined that adaptive capacity is sufficient, then adaptive measures may be focused on addressing other aspects of vulnerability (i.e., sensitivity or exposure). However, where there are deficits in capacity or barriers to adaptation, these will need to be addressed. Williamson and Isaac (2013) review some management options to address insufficient capacity or adaptation barriers; however, they stress that any options undertaken must be feasible and tailored to the SFM system being assessed.

Once vulnerabilities are determined, adaptation options can be identified that reduce the exposure or sensitivity of SFM to climate change and (or) build up adaptive capacity over time — both processes that reduce vulnerability. The costs and benefits of different adaptation options can be estimated and compared among the range of scenarios to identify "no-regret" measures (i.e., beneficial even in the absence of climate change), "low-regret" measures (i.e., where the cost is low relative to the costs of possible impacts that would be avoided), and "robust" measures (i.e., those that require greater expenditure but will produce net benefits across all scenarios).

Additionally, there are potential trade-offs and synergies between adaptation and mitigation options that may need to be considered, particularly at the intersection of energy alternatives, carbon sequestration, and natural resource management (Nabuurs et al. 2007). Research will continue to explore these potential conflicts and complementarities, recognizing that the best adaptation options are likely to vary with both geographic and economic factors. Clearly, there is much to be learned, and much that will remain uncertain, as adaptation strategies are developed and tested. Scenarios can be a valuable tool to explore how complementary adaptation and mitigation strategies may be implemented to optimize the benefits and minimize the negative effects (e.g., see Locatelli et al. 2010).

Case Studies: Using Scenarios to Assess Impacts of Climate Change on Sustainable Forest Management

The Forest Futures Project

Seeking to inform Canadian forest policy and planning, the Sustainable Forest Management Network initiated a project to engage researchers, forestry stakeholders, and others in an analysis of the future of Canada's forests and forest sector (Duinker 2008). Seventeen workshops were held in 15 communities across Canada, four of which were national in scope and aimed to engage specific groups, including the Sustainable Forest Management Network, First Nations, and academics involved in the Forest Futures Project (FFP) (K. McKenzie, C. Frittaion, and P. Duinker. 2010. Synthesis of results of regional workshops. Dalhousie University, Halifax, NS. Unpublished report.). The other 13 workshops were regionally focused and attracted various stakeholders who were involved or interested in forests and the forest sector. Early workshops centered on developing the scenarios, while those occurring later in the project concentrated on testing scenario plausibility and discussing their implications.

Using a participatory process, participants in the FFP identified the following 13 drivers of change in the Canadian forest sector: global climate change; global forest products demand and Canadian wood supply; invasive species; geopolitics; global energy; technology; governance; aboriginal empowerment; air pollution; conflict over resources; society's value for forests; demographics; and industry profitability. For each of the 13 drivers, a paper was researched and drafted to discuss the influence of that one driver on the forest sector and its future trends (these papers are available at http://www.sfmn.ales.ualberta.ca/Research/ForestFutures/ForestFuturesDocuments.aspx). Two drivers, namely environmental change and society's value for forests, were considered to be particularly influential but uncertain, and were selected as the basis of the scenarios. The matrix approach was used to distinguish among four possible futures that differed in terms of the trajectories of these two key drivers, with a representative scenario from each quadrant assigned an appropriate name (Fig. 9). Each scenario was developed using a common structure that described a specific future, and the responses of the other 11 drivers to the two key drivers (i.e., changes in the natural environment and in the societal values placed on forests). Each scenario was then written as a "future history" that described the period 2000–2050 in the past tense. Papers describing each of the four scenarios are also available on the project website along with a table that compares the trends in each of the drivers among the four scenarios.

The mean duration of workshops was 6–7 h, and 10–60 participants normally attended each workshop (described in Frittaion et al. 2011). The lead facilitator, who was usually a member of the project team, described scenario analysis, the FFP, and how the four representative scenarios were developed. Next, participants would separate into smaller groups to discuss possible local implications and responses to two of the four scenarios.

Participants expressed a variety of reactions to the scenarios, including hopefulness,

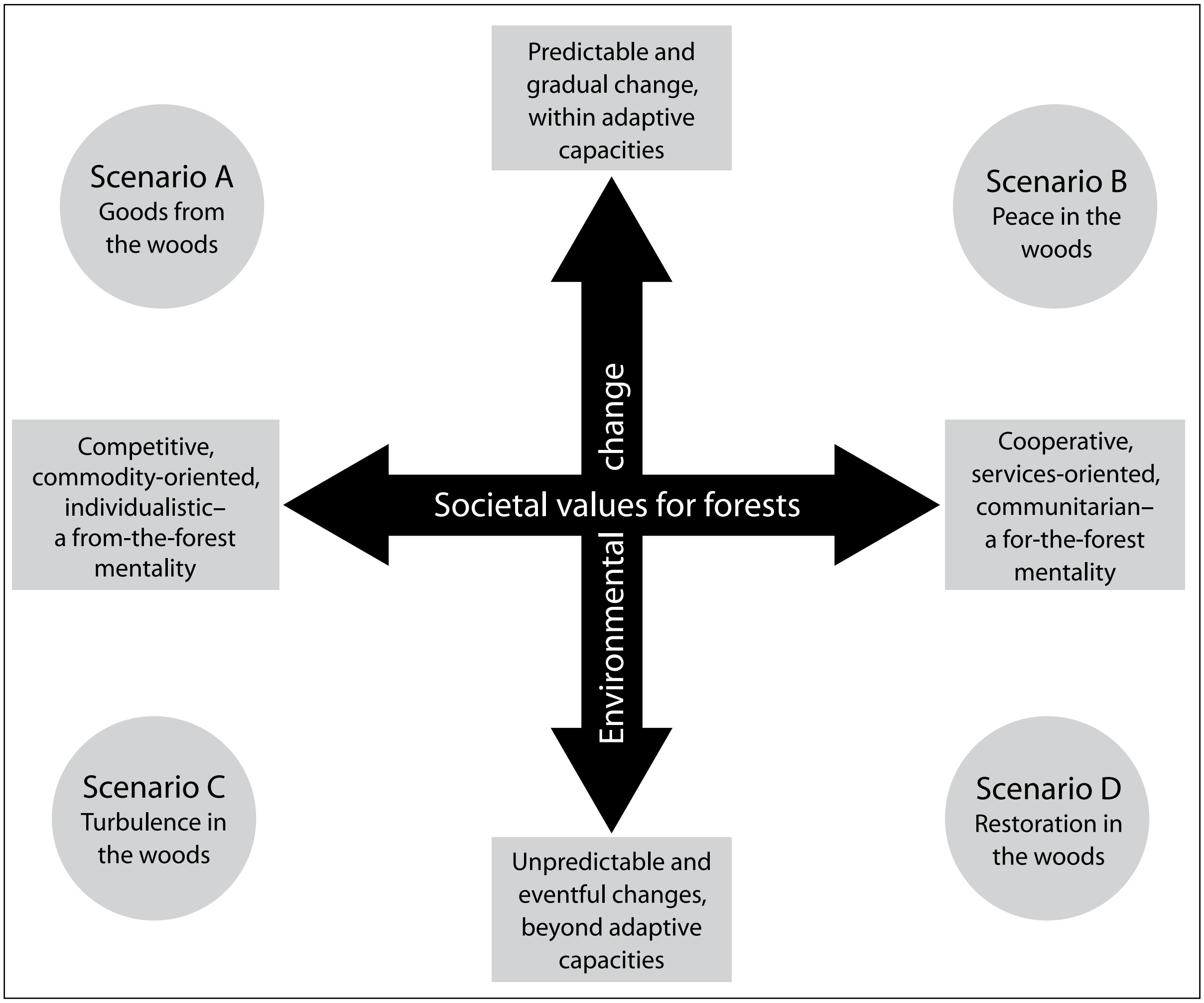

Figure 9. The Forest Futures Project matrix and four representative scenarios, from Duinker (2008) used with permission.

hopelessness, and disbelief (K. McKenzie, C. Frittaion, and P. Duinker. 2010. Synthesis of results of regional workshops. Dalhousie University, Halifax, N.S. Unpublished report.). In particular, two scenarios were found to evoke the strongest reactions: Peace in the Woods (viewed with greater scepticism, but also seen as the most desirable) and Turbulence in the Woods (considered as more likely, yet highly undesirable). The time required to become comfortable with scenario analysis and to suspend belief (i.e., to abandon scepticism and accept the possibility that any scenario could come to pass) also varied (Frittaion et al. 2011).

McKenzie et al. (K. McKenzie, C. Frittaion, and P. Duinker. 2010. Synthesis of results of regional workshops. Dalhousie University, Halifax, NS. Unpublished report.) summarized the common themes that emerged from workshop discussions, which included forest management, forest values, economics, and ownership. While perspectives differed on the details, there was general consensus that there would be an increased need for forest management in the future as well as a shift toward management for broader forest values and a greater diversity of products. Participants identified some of the required inputs to meet this future as follows: improved training for forest managers on a broader range of topics; increased science-based management; better metrics and increased acceptance of new normals (i.e., shifting away from an emphasis on maintaining current conditions); and better incentives for collaboration and resolving disputes (e.g., between environmental and industrial lobbyists). Participants also speculated that changes in the economy and in environmental conditions would devalue some forests while presenting new opportunities for others, although there was little agreement on where and how such events might occur.

Implementation of new policies was frequently discussed as a mechanism for supporting social change. Policy leadership at multiple levels was identified as necessary for achieving good policy, although participants often thought that locally determined policy would be a particularly good approach to addressing future forest sector difficulties. However, challenges with local capacity, such as a lack or decline of expertise in rural areas, were often acknowledged. The need for flexible policies was also emphasized, especially as a way to accommodate an increasing diversity of uses for forests and forest land, though the potential for increased conflict was identified as a potential area of concern.

Although most participants considered future-oriented thinking to be important, many were also critical of the scenario process, arguing that it took time away from dealing with the critical state of the forestry sector in order to "play". McKenzie et al. (K. McKenzie, C. Frittaion, and P. Duinker. 2010. Synthesis of results of regional workshops. Dalhousie University, Halifax, NS. Unpublished report.) note, however, that participants from opposing groups (e.g., industry and environmental NGOs) were generally able to find common ground. For instance, many participants recognized that they will be affected by a common set of drivers and future conditions, and even though they did not necessarily agree on a desired future state or a shared response, many were able to see that they faced collective challenges. Interestingly, cooperation was most often identified as a requirement to address challenges, but participants frequently had difficulty believing that cooperation was likely or even possible.

Vanderhoof forest-based community, British Columbia

The community of Vanderhoof is located in the central interior of British Columbia, with a population of about 4400 in the town and a further 12 000 in outlying regions. Forestry is the largest economic sector. Williamson et al. (2008) assessed the potential biophysical impacts of climate change on local forest resources and the consequent socioeconomic impacts to the community while also summarizing some potential economic implications of climate change for agriculture, water resources, fisheries, outdoor recreation, and tourism. The Vanderhoof forest region is near the epicentre of the mountain pine beetle (MPB) outbreak, which has caused unprecedented losses of lodgepole pine timber, estimated at 700 million m^3 extending over more than 17 million ha in British Columbia (B.C. Ministry of Forests, Lands, and Natural Resource Operations 2014). The current outbreak has been partially attributed to a series of warmer than normal winters in the late 1990s and early 2000s (e.g., Safranyik et al. 2010). Climate data from Environment Canada extending back to 1901, supplemented by data from local B.C. Hydro climate stations, established that a general warming trend occurred during the 20th century, with the 1990s being the warmest decade on average. Local residents also reported personal observations of recent changes in climate, such as more abrupt and severe storms, shorter winter logging seasons, increased stream flows in spring, and shallower snowpack in the valley.

Scenarios of future climate had been developed previously from global projections obtained for three GCMs (Canadian CGCM2, UK HadCM3, and Australian CSIRO Mk2) forced by each of two SRES scenarios (the more pessimistic A2 and more optimistic B2). Each projection was combined with observed climate normal data for 1961–1990 to create six scenarios of future climate. Of these, three distinct scenarios were selected to cover the Vanderhoof study region and dubbed warm and dry, cool and dry, and hot and wet, corresponding to the CGCM2 forced by the A2, HadCM3 forced by the B2, and CSIRO Mk2 forced by the A2, respectively.

Several trends were consistent across all GCMs and GHG scenarios. All scenarios indicated that by 2100, mean daily minimum temperatures would increase more than the daily maxima (from 1.5 to 6.0 °C compared with from 1.0 to 4.0 °C, respectively) and that temperatures in winter would increase considerably more than in summer. All three GCMs projected increases in annual precipitation, with the largest occurring in the summer. As expected, all GCMs projected greater mean warming when forced with the A2 GHG scenario than with the B2.

A process-based vegetation model was used to project how forest composition and productivity in the Vanderhoof study area might change under the three different climate scenarios. The Canadian Integrated Biosphere Simulator (Can-IBIS), derived from the IBiS model of Foley et al. (1996), captures climatic responses of forest vegetation to key environmental variables, including climate, atmospheric CO_2 concentration, and soil factors. Can-IBIS was used to project changes in forest composition, productivity, and standing biomass represented as mixtures of plant functional types (including boreal and temperate needleleaf and broadleaf forest types). The model was first validated using historical climate data to see how well it would simulate forest structure in the Vanderhoof region ca. 2000, not accounting for the effects of MPB. Overall, the results were reasonably accurate, although the simulated landscape could only be considered an approximation of the real forest, which is largely dominated by a mixture of pine and spruce with relatively low deciduous content. The projections of future forest composition were similar for the "warm and dry" and "cool and dry" scenarios, with only minor changes occurring by 2100. The warmer and drier scenario produced slightly more temperate conifer (indicative of species such as interior Douglas-fir and lodgepole pine). The "hot and wet" scenario caused forest composition to shift towards a larger fraction of deciduous broad-leaved species along with increased conifer volume. Standing timber volume was projected to increase significantly in all three scenarios, although the greatest increases were projected to occur with the "cool and dry" conditions projected by the HadCM3 GCM forced by the B2 scenario.

Williamson et al. (2008) cautioned that these forest projections should be treated with skepticism because they represent highly uncertain changes and do not account for unexpected surprises. For instance, projected volumes of standing timber for 2100 are representative of changes in temperature and precipitation, but do not reflect other possible climate change effects such as more intense storms, which have the potential to cause significant timber losses. Additionally, losses from fire and insect outbreaks, including MPB, were not reflected in the Can-IBIS projections. Events on the scale of the MPB outbreak are unprecedented in recorded history and have the potential to create completely unanticipated consequences on both forest ecosystems and dependent communities.

To assess the impacts of climate change on fire susceptibility in the Vanderhoof study area, Williamson et al. (2008) used a landscape simulation model (BURN-P3) to project forest conditions in 2041–2060. Regional vegetation and climate data were used to produce four scenarios for model analysis (two for the current period and two for the future period). These were (1) a baseline (fuel inputs consistent with conditions before the MPB outbreak and baseline weather conditions observed from 1985 to 2004); (2) current conditions (high fuel flammability conditions from 2004 owing to MPB and baseline weather conditions); (3) low flammability and no climate change (beetle-killed timber returns to a low-flammability state by the future period with baseline weather conditions); and (4) low flammability with climate change (weather conditions projected by CGCM2 forced by SRES B2). Only a single set of climate change projections was used, selected on the basis that it produced the most extreme changes in fire weather for the period 2041–2060. Fire susceptibility before the MPB outbreak was categorized as low for 79% of the study area, but the model indicated large increases in the areas with moderate, high, and extremely high fire susceptibility, due to increased fuel-loading following widespread mortality caused by MPB. In the future, with no change in climate, the MPB-affected areas were projected to return to lower flammability, causing fire susceptibility to generally decrease. On the other hand, even if the MPB-affected areas returned to low flammability, the climate scenario would cause a general increase in fire susceptibility, though not as high as it became in the period immediately following the MPB outbreak.

The future economic impacts of climate change on the local economy of Vanderhoof were evaluated using a general equilibrium model to project potential changes in forest sector exports from the Prince George Timber Supply Area between 2000 and 2055. The model represents a small open economy consisting of six sectors (agriculture, forestry, services, the public sector, tourism, and "others") whose production is based upon three inputs (labor, land, and capital). Potential changes in labor and household income were analyzed using several simplifying assumptions. First, both the structure of the economy (growth, structural adjustment, new capital investment) and the amount of land available for production were fixed over the period examined. Second, changes in timber supply were considered to be uniform across the Prince George Timber Supply Area. Finally a 1:1 ratio was used to convert changes in timber supply to equivalent changes in timber harvests and exports. This ratio assumed that domestic timber demand was fully satisfied and did not change over time, such that any change in timber supply would cause an equivalent change in exports.

Four scenarios of socioeconomic development were used to project future economic conditions for Vanderhoof. These scenarios were developed by considering possible changes in climate (according to the A2 and B2 emissions scenarios) and in global market conditions (favorable and unfavorable).

Changes in timber supply were simulated for the year 2055 using a combination of best- and worst-case projections for MPB-caused mortality together with increases in forest productivity derived from the Can-IBIS projections reviewed earlier. A comparison of the results indicated that the positive growth effects of climate change over the next 50 years could offset some of the supply losses arising from MPB, but annual allowable cut (AAC) for the Vanderhoof Forest District would still be lower than the pre-beetle AAC by 2055.

Changes in the supply and cost of labor were analyzed separately (assuming either fixed wages and variable supply or full employment and variable wages) for several time periods under different harvest levels. The associated changes in aggregate household income resulting from labor fluctuations were also assessed. Economic impacts for the forest sector in the Prince George Timber Supply Area as a whole were variable over time, with 4%–30% increases (relative to the year 2000) in household income early on resulting from increased salvage operations, followed by decreases of 1%–7% in the 2015–2020 period and a slight recovery over the long term (projected by 2055 to range from 5% above to 4% below the mean household income in 2000). As the level of beetle-caused tree mortality experienced in the Vanderhoof forest district was more severe than that experienced by the larger Prince George Timber Supply Area, Williamson et al. (2008) suggested that the immediate economic benefits from early salvage logging, and the economic downturn from reduced AAC in the medium term may be more severe in the Vanderhoof forest district. Longer term impacts (for 2055–2100) for Vanderhoof's forest sector became more uncertain as the projected changes in climate became more extreme, causing both increased and decreased timber supply by 2100. Overall, increased economic volatility was anticipated.

In the final stage of the analysis, the results of the biophysical and socioeconomic analyses were combined to create four integrated impacts scenarios for Vanderhoof in 2050 (Fig. 10). Each scenario represents either moderate or significant climate change combined with strong or weak socioeconomic development. Scenario 1 reflects strong global and local economies, moderate climate change (HadCM3 GCM forced by the SRES B2 emissions scenario), minor climatic impacts on forest composition, forest ecosystem productivity increase of 23%, and markedly higher fire susceptibility. Scenario 2 represents strong global and local economies, significant climate change (CGCM2 forced by SRES A2), small changes in forest composition, forest productivity increased by 34%, but a smaller increase in fire susceptibility compared with that of Scenario 1. Scenario 3 signals weak global and local economies, moderate climate change (HadCM3 forced by SRES B2), minor impacts on forest composition and productivity (12% increase), and an increase in fire susceptibility equivalent to that of Scenario 1. Scenario 4 reflects weak global and local economies, significant climate change (CSIRO2 forced by SRES A2), a significant increase in broadleaf species, forest productivity increased by 30%, and moderate increases in fire susceptibility.

Millar Western Forest Products Ltd. Cumulative Impacts Study

Millar Western carried out a cumulative impacts study to examine the interacting effects of key drivers on annual harvest levels in a forest management unit — the Millar Western Defined Forest Area (DFA) (Yamasaki et al. 2008; see

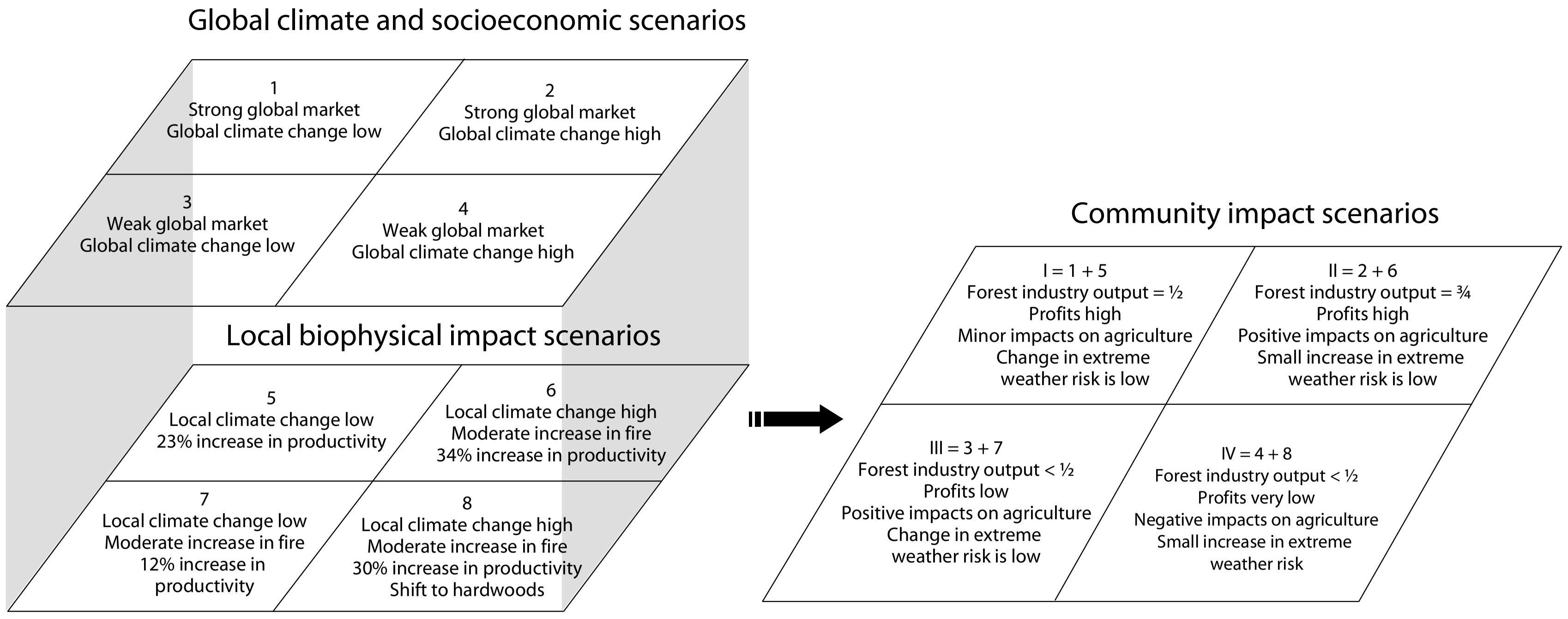

Figure 10. Example framework from the case study of the Vanderhoof forest-based community. Scenarios of global climate change and socioeconomic drivers with local-scale biophysical and socioeconomic impacts. Reproduced from Williamson et al. (2008); reprinted with permission of the publisher.

also Appendices 19 and 20 of the detailed forest management plan at http://esrd.alberta.ca/lands-forests/forest-management/forest-management-plans/millar-western-forest-products.aspx). The objective was to assess the impacts of climate change and other factors (including occurrence of wildfires, increases in local human population, and the effects of oil and gas developments) on AAC for the DFA. A baseline simulation projected future harvesting levels assuming no changes in conditions, and eight alternative scenarios considered various combinations of the different (often interacting) factors applied over a 200-year projection period.

As climate change was only one of several factors considered, the authors selected a single climate projection generated by the Japanese CCSR-NIES GCM (Centre for Climate System Research – National Institute for Environmental Studies), forced by the extreme SRES A1 GHG emissions scenario, so that the effects of severe climate changes on forest growth and fire occurrence could be assessed in comparison to the effects of the other key drivers. Thirty years of daily climate data for 1961–1990, interpolated to 150 local townships (~10 km × 10 km squares) covering the DFA, were used as baseline climate. Mean projected changes in climate were extracted from the GCM projection and combined with the daily data for 1961–1990 to create the forcing climate scenario: 30 years of future daily climate data (representing the late 21st century).

A stand-level forest model (FORECAST, developed by Kimmins et al. 1999) was used to simulate growth in volume and changes in species composition. The potential effects of climate change and increasing CO_2 concentration on productivity were simulated with additional climate-sensitive submodels of photosynthesis and decomposition (Duchesneau et al. 2006), to estimate effects of climate change on representative stand types. The FORECAST model was initialized using local forest inventory data, and results were matched (using basal areas of leading species in 40-year age classes) to individual stand polygons. Productivity for each of these polygons was also simulated for future climate conditions, including the scenario of CO_2 concentration increase developed for SRES A1. The FORECAST model also represented changes in dominant species based on whether the stand was regenerated following harvesting or following fire.

The daily data for 1961–1990 and the future climate scenario were also used to estimate daily fire weather indices for the 150 townships for both historical and future periods. The fire weather index data were then used to estimate the annual occurrence of days with high fire weather index and hence project how the frequency of fire events (number per year) might increase in the future. Effects of human population growth on fire occurrence were included, recognizing that fires caused by humans have been a significant hazard in the past. Areas burned were simulated using two different submodels of fire occurrence and propagation across the landscape. Losses of forest land base to oil and gas developments included simulations of seismic line exploration, projections of increases in the number of wells established in each township, and of the consequent growth in the network of pipelines across the DFA.

A larger scale integrating model termed the Athabascan Plains Landscape Model was constructed to simulate potential landscape-scale changes in harvestable timber volume in the DFA. The Athabascan Plains Landscape Model used results from the FORECAST stand polygon simulations combined with depletions of forest area due to alternative combinations of oil and gas developments and fire occurrence (the latter with and without population change effects imposed). These simulations were repeated with the climate change scenario effects imposed on forest productivity and on fire occurrence. When the scenarios of future fire, population growth and oil and gas exploration were introduced, the effects on AAC and harvestable area (and volume production, including salvage where applicable) were calculated. Effects on ecosystem biodiversity related to stand age and fragmentation were also investigated. In total, nine scenarios were examined, with the “harvesting only” scenario treated as the baseline (since it provided the highest AAC under current climate conditions), with various combinations of fire occurrence, population increase, oil and gas exploration, and climate change providing a further eight scenarios.

The results of the cumulative impact assessment showed that climate change and population growth could intensify the impacts of fire on forest ecosystem values. In general, the combined effects of climate change and oil and gas development were found to reduce AAC. Merchantable timber volume per hectare was found to increase by about 20% in response to beneficial effects of the climate change assumptions on productivity. However, these gains would be more than offset by increased fire occurrence as a major cause of reductions in AAC. The additional effects of oil and gas development and human population growth had relatively marginal impacts. These results were integrated into a novel forest management plan that considers the cumulative impact of these potential changes in planning and carrying out SFM (Millar Western Forest Products Ltd. 2008), and hence provides an example of mainstreaming climate change considerations into management planning.

National Round Table on the Environment and the Economy: Climate Prosperity

The NRTEE estimated the future economic costs of climate change for Canada using both top-down economic analysis and bottom-up estimates for three sectors of impact (timber supply, coastal areas, and human health) (NRTEE 2011). For the first analysis, they identified two driving forces that would determine the magnitude of economic costs, namely the extent of climate change resulting from increasing global GHG emissions and growth of Canada's economy and population. The level of future climate change considered was based upon the IPCC SRES low (B1) and high (A2) estimates of future GHG emissions (Nakićenović et al. 2000). The range of national economic and population growth considered was based on the UK Climate Impacts Program (2000) low (local stewardship) and high (world markets) global socioeconomic development scenarios adapted to the Canadian context. By combining these two driving factors, four scenarios of the future were generated for Canada (see Table 3).

A global economic model called PAGE (Policy Analysis of the Greenhouse Effect) was used to estimate sea-level rise and the amount of warming that would occur in Canada under each of the two climate scenarios. The model monetizes impacts to traditional economic sectors, some noneconomic costs such as health and ecosystem impacts, costs from sea-level rise, and costs from catastrophic damage. A price of about 2% of annual GDP for warming of 3 °C was used to calculate global costs under each of the four scenarios, although national estimates vary according to relative wealth, population, forecast temperature change, and vulnerability to climate change.

The costs of climate change for Canada were estimated (2008 dollars, not discounted) for each scenario at the near, medium, and long term (2020s, 2050s, and 2080s, respectively). In all cases, the costs of climate change accelerate with time. The near-term estimates

Table 3. Summary of scenarios adopted for the National Round Table on the Environment and the Economy study on Canadian climate prosperity (NRTEE 2011)

Driver	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Climate change	Low (Canada's MAT increases 4.3 °C by 2075)	High (Canada's MAT increases 5.3 °C by 2075)	Low (Canada's MAT increases 4.3 °C by 2075)	High (Canada's MAT increases 5.3 °C by 2075)
Socio-economic change	Low (national GDP growth of 1.3% annually; population reaches 41 million by 2050; 52 million by 2100)	Low (national GDP growth of 1.3% annually; population reaches 41 million by 2050; 52 million by 2100)	High (national GDP growth of 3% annually; population reaches 46 million by 2050; 58 million by 2100)	High (national GDP growth of 3% annually; population reaches 46 million by 2050; 58 million by 2100)

Note that in the study, economic growth and population growth were combined as two attributes of a single driver (i.e., low growth or high growth).
MAT = mean annual temperature.

are very similar under all scenarios (mean annual costs of $5 billion by 2020), as there is high confidence in immediate forecasts of emissions, temperature increases, economic performance, and population trends; by 2050, however, the estimates of annual costs range from $21 to $43 billion (0.8%–1% of GDP). In the long term, annual cost estimates under each scenario become increasingly different, as the disparities between the impacts of low (small temperature increase) and high (large temperature increase) climate change become even larger. With slow growth and the low GHG emissions scenario, mean annual costs in 2075 are estimated at $51 billion compared with $221 billion under the high GHG emissions and rapid growth scenario.

The NRTEE study also attempted to quantify the effects of extreme scenario uncertainty in dollar terms. They concluded that there is relatively little chance that costs would be either lower or higher than the range projected. However, the report stresses the need to consider the possibility of both high likelihood costs and more costly impacts that appear less likely. For example, there was an estimated 5% chance that annual costs could be less than $16 billion or greater than $91 billion by 2050. Similarly, for 2075, there was a 5% chance that costs could be as high as $546 billion and a 1% chance that they could reach $820 billion.

The bottom-up analysis of climate change impacts on timber supply concentrated on supply shifts caused by changes in forest fire regimes, forest productivity, and pest disturbances brought about by climate change. Timber production in six regions (namely British Columbia, Alberta, Ontario, Quebec, Atlantic Canada, and a central region comprising Manitoba, Saskatchewan, and the territories) was examined using a CGE model. The regional models were built using 2004 data from Statistics Canada for inputs, and several outputs were generated (for timber and nontimber harvesting, timber production, reforestation, logging, pulp and paper production, and wood products manufacturing). The models were then used to estimate future regional economic baselines in 2020, 2050, and 2080 for each region under both the slow and rapid socioeconomic development scenarios using forecasts from Infometrica (http://www.infometrica.com/) that were scaled appropriately.

Climate projections from four GCMs were used to create scenarios of regional temperature changes for the SRES A2 and B1 GHG emissions scenarios. Forest sector outputs were adjusted based on the regional estimates of changes in timber supply due to effects of climate change, including increased area burned by fires, increased pest infestations, and changes in forest productivity. The process used to develop both optimistic and pessimistic scenarios of net timber impacts for each region is described in detail in Marbek and van Lantz (2010). The percent changes in timber supply from each regional scenario were equated with an equal percent change in economic output used to run the models. The model runs projected changes in selected economic indicators under climate change, and by comparing them with the regional baselines (without climate change), the economic impacts of different climate futures were calculated.

The impacts of climate change on timber supply (net losses) increased over time in all regions, although this effect was more pronounced in western regions than in the east. Compared with the contribution of forestry to national GDP without climate change, the net impact would be a decrease of $2.4 and $17.4 billion (0.12%–0.33% less) by 2050. By the 2080s, the contribution of forestry to national GDP would be between 0.11% and 0.15% lower than it would be without impacts on timber supply induced by climate change. In cumulative terms, GDP losses due to climate change impacts on forestry were estimated to be in the range of $25–$176 billion nationally by 2080.

The bottom-up analysis also looked at the possible reduction in impacts that would result from the combined effects of three adaptations: (1) enhancing forest fire prevention, control, and suppression; (2) increasing pest prevention and control; and (3) planting tree species better suited to future conditions. The six regional CGE models were run with adjusted changes in forest sector output that accounted for the effects of adaptation (see Marbek and van Lantz 2010). These reductions in the negative economic impacts of climate change were then compared with the costs of implementation. The results indicate that the benefits of adaptation outweigh the costs in every region under every scenario; however, the uncertainty regarding the costs of implementation and the effectiveness of different adaptations is appreciable, and the assumptions made in the analysis may be overly optimistic given recent experiences with MPB.

Case Study Comparison and Synthesis

The case studies reviewed here all made use of scenarios, but in other respects there were few, if any, similarities in their approaches, which demonstrates that there are many ways to use scenarios and carry out scenario analyses.

Both NRTEE and FFP were national in scope, but NRTEE attempted to be quantitative, focusing on multi-sectoral economic impacts, whereas FFP was highly qualitative and focused on forests and forestry. However, the FFP was also extremely comprehensive in identifying multiple drivers and considering their potential and interacting impacts. Conversely, the Millar Western and Vanderhoof studies were focused on much smaller regions: a single forest management unit and a forest-based community, respectively. The Millar Western analysis contributed to the periodic update of the detailed management plan and addressed only those drivers identified by local forest managers as being most important. The local community that initiated the Vanderhoof study invited specialists from "outside" to choose the scenarios and perform the modeling and data analysis, but also remained actively engaged in the process. Hence, the Vanderhoof study was broader in scope, covering a larger region, and addressed social and economic impacts as much as the biophysical effects of climate change. The NRTEE and Vanderhoof case studies were both relatively unusual for their explicit consideration of economic and social impacts.

The FFP used a mainly participatory approach where academics and other specialists engaged with stakeholders in multiple workshops. Dialogue among forest stakeholders with varied interests and backgrounds was encouraged; while no consensus was reached on what the specific impacts would be, recommendations about what needed to be done to respond to future impacts were identified. FFP engaged many experts but was not focused on quantifying or modeling changes as much as understanding the potential for change and how that might impact forestry more generally. The other studies were more research oriented. In particular, the Vanderhoof study was a hybrid of quantitative modeling for biophysical and economic impacts, but used interviews with residents and stakeholders, as well as participatory workshops for information exchange. Important objectives were to share expert knowledge with local players to enhance understanding of the range of possible impacts and to engage people more in the decision-making progress.

The scenario-axis approach was adopted in three of the four case studies (Millar Western being the exception). The Vanderhoof study used three distinct scenarios of future climate to assess possible biophysical impacts, but used the scenario-axis method to explore socioeconomic impacts. The NRTEE study adopted two global scenarios of climate change and associated socioeconomic changes derived from the IPCC AR4, although more GCM scenarios were used to assess climate change impacts on timber supply. The FFP used global climate change as one key driver of the future scenarios, but it was treated subjectively with no reference to specific GCM projections.

Millar Western used a more conventional sensitivity analysis approach that looked at the impacts of different drivers individually. The climate change scenarios were limited to a binary condition: no change in climate or extreme change in climate. The Millar Western study was one of very few examples where scenario analysis has led to climate change considerations being mainstreamed into long-term management planning.

As a final observation, this selection of case studies demonstrates that scenarios can be analyzed using a variety of methods at a range of scales that depend on the focus of the project. Hence, it is important to recognize that the selection of specific methods of scenario creation and analysis, and their use, must be based on the context of the vulnerability assessment. The criteria include the scale of the system of interest, its geographic location, and the particular aspects of local management for which adaptations are anticipated.

CONCLUSIONS

This report reviews what scenarios are, how they are relevant to SFM, and how they can be used in assessments of vulnerability to climate change. The wider aspects of scenarios and scenario analysis used in impact assessment are discussed, working both down from, and up to, the national and global scales. However, we focus on obtaining and applying scenarios at the scale of a forest management unit, to support the adaptation of SFM systems to a changing climate. Scenario analysis is an emerging discipline aimed at interpreting and comparing multiple views of the future and using this to guide strategic decision making (e.g., see Mora et al. 2013). It is important for SFM practitioners to recognize the value in scenarios and to begin to carry out scenario analyses as a means of exploring management options. This application to SFM may be in its early stages, but even with the current limitations and uncertainties inherent in biophysical and socioeconomic scenarios, it should be recognized that adaptive management (a critical element of SFM) is all about learning and adapting as environmental conditions change over time. Developing and analyzing scenarios can be a valuable part of the learning process.

Scenarios provide a linkage between global projections of changes in climate and socioeconomic conditions and the potential impacts of these changes at local scales. The global scenarios capture the efforts of hundreds of researchers in the biophysical and social sciences and provide essential information about the range of potential impacts at local scales. However, the development of scenarios for SFM must also account for local factors, some of which are likely to be more important drivers of vulnerability and may need to be addressed if adaptation efforts are to succeed.

The traditional approach to analysis of climate change impacts on biophysical and socioeconomic systems has been to create global scenarios of future socioeconomic development as a driver of GHG emissions and associated climate change, and then to examine the consequences as a stepwise linear process: on global climate, on the biosphere, and then on society (e.g., see Fig. 2). In the past, assessments have tended to limit the number of scenarios and assume that future trends in social and economic development will continue linearly from the recent past. The major objection to this approach is that vulnerability to climate change can have multiple causes and a single scenario is insufficient to explore the range of these causes. Further, relying on a single "story of the future" may hide many sources of uncertainty (Berkhout and van Drunen 2007). Placing trust in the potential outcomes from a single story could lead to the development of adaptation strategies that would be inappropriate and inflexible. Further, such an approach cannot account for societal feedbacks (such as changes in economic status and the effects of human adaptations) in response to the projected changes in climate (see Fig. 7).

The current thinking is to explore multiple distinct scenarios of future climate and socioeconomic development, and to represent the interrelationships among social development and climate change in a more dynamic and integrated way. The interactions among climate change effects and other environmental changes (notably land use pressures), and the consequences of planned adaptations, need to be part of the assessment of local vulnerability. A more interdisciplinary approach to scenario development also facilitates investigating the effects of possible mitigation and adaptation actions.

Many assessments of the impacts of climate change on forests have explored only the biophysical impacts of alternative scenarios of future climate, but SFM is as much about social and economic sustainability as it is about sustainable forests. This suggests that an interdisciplinary approach to assessments is needed that takes forest management governance and decision making into account (Cohen and Waddell 2009), and which therefore must include socioeconomic impacts. Given differences among GCMs and their simulated responses to different levels of GHG forcing, an assessment should use a minimum of three climate scenarios: these could generally be classified as "cool" (meaning projected temperature increases are at the low end of the range), “warm and dry” (projected temperature changes are high, but coupled with little change in precipitation), and “warm and moist” (large temperature increases are coupled with significant increases in precipitation). There are likely to be marginal gains from using more than three scenarios selected to cover this range of possibilities.

It is critical to recognize limitations in the biophysical models and in the scenarios of biophysical impacts that these models produce. More effort in local scenario development can be directed at other questions, including the social and economic consequences of global and national population growth, land use change, and emerging technologies (e.g., the use of forests as biochemical feedstocks or bioenergy), as well as the possible effects of economic shocks.

As has been discussed here and elsewhere (e.g., Johnston et al. 2010b; Williamson et al. 2008), more effort may be needed to develop the capacity of SFM in Canada to adapt to the impacts of climate change. Williamson and Isaac (2013) suggest that this need is sufficiently acute that managers should begin to consider those needs today, so that adaptive capacity can begin to be built where it will be most needed in the future. The present report only briefly discusses the importance of considering adaptive capacity in a vulnerability assessment for SFM.

Further, the discussion here suggests that better understanding of the effects of climate change on human adaptive capacity may also be required. While one might assume that adaptive capacity within Canada will only increase as more information about climate change and its impacts becomes available, there is also the possibility that the effects of climate change could become severe enough to overwhelm adaptive capacity over a wide area. This could result either from a gradual accumulation of impacts or from one or more catastrophic events.

Finally, it is important to recognize that, regardless of how imperfect models and scenarios may be, they are still valuable for their capacity to stimulate discussion, both for climatic change and its diverse array of impacts. Berkhout and van Drunen (2007) suggest that qualitative analysis and participatory approaches should be given a more prominent role in impacts analysis (see also Cohen and Waddell 2009). Climate assessments should be understood as a joint learning process between researchers and stakeholders, with the objective of understanding and communicating how impacts occur and how measures can be implemented most effectively to adapt to those impacts or avoid them. This approach also favors starting from the social and economic conditions of importance and then inserting climate change effects as a new variable — opposite in philosophy from the common perception that analyses should start with the physical sciences (climatology) and progress towards identifying important impacts using biological sciences (ecology) and social sciences (sociology and economics).

The participatory approach to futures analysis is increasingly recognized as beneficial, because even though quantitative models and scenarios can provide important focus, it is the discussion of what they represent that is really valuable (e.g., Shackley and Deanwood 2003). Making different world views and preconceptions explicit and allowing these perceptions to be questioned, or presenting alternatives to commonly held beliefs, appears to be particularly valuable. In this way, futures analysis can build capacity and anchor vulnerability assessments in local decision making (Naess et al. 2006). Such open discussion is also valuable to SFM more broadly, in that balancing multiple benefits from forests for current and future generations is a complex challenge requiring that participants with divergent views and values consider implications for sustainability. If a community or management group can gather to discuss the range of views and values affecting decision making, this collaboration helps enormously in building adaptive capacity: people begin thinking about the possibilities, open their eyes to what may happen, and hence engage in creative thinking about adaptation —a process that otherwise might not have happened. Given this function, the origin of the scenarios used to frame the discussions about adaptation may prove to be less important than the fact that the necessary brainstorming actually occurs. Discussion can reveal the possibility space for the future and lead to more robust decision making.

Some overarching principles and caveats for selecting and using scenarios include the following:

- the future is unknowable and uncertain; uncertainty stems both from an inability to predict future human activities (irreducible uncertainty) and from incomplete knowledge of how the natural world functions (reducible uncertainty)
- uncertainty about climate change and its impacts will increase with time into the future
- uncertainties are cumulative (human behavior → impacts on climate → impacts on natural systems and human infrastructure → impacts on people) (see Fig. 2)
- using multiple scenarios of the future helps an assessment to capture the range of uncertainty
- consistency among social and economic development assumptions, GHG emissions, climate projections, and forest and socioeconomic responses supports more rigorous comparisons among different scenarios
- use all scenarios (and the models that create them or use them) with caution; subject all results to careful scrutiny
- be prepared for surprises or gaps in knowledge (i.e., not captured by models or scenarios) that require further investigation
- when undertaking a vulnerability assessment, participation of both stakeholders (who can identify the important questions) and researchers (who can provide expertise in data gathering, modeling, and analysis) is essential in the development of plausible and relevant scenarios

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APPENDIX 1

Inventory of Socioeconomic Scenarios

Global Scenarios

Global Scenario Group

The Global Scenario Group was initiated by the Tellus Institute and the Stockholm Environment Institute in 1995 to examine scenarios of global development with the goal of fostering a more sustainable and equitable future (http://www.gsg.org/index.html). Their research focuses on the driving forces, critical uncertainties, and impacts of stress on social and environmental systems using an extensive database and computing framework called PoleStar (http://www.polestarproject.org/polestar_sys.html). This work attempts to identify the policies, values, institutions, technologies, and lifestyles that are required to achieve a sustainable future (see Raskin et al. 1998, 2002, 2010; and http://www.gtinitiative.org/).

Three sets of scenarios were developed for the 21st century, named Conventional Worlds, Barbarization, and Great Transitions, each containing a business-as-usual baseline and a variant (Gallopin et al. 1997; see Fig. A1.1). The Conventional Worlds scenarios reflect incremental industrialization following current trends, together with growth in production and consumption in developing countries to levels similar to those in developed nations. The reference scenario is based on mid-range population and development projections and standard assumptions about technological change. Social and environmental stresses associated with global population and economic growth are assumed to be governed by a free market. The Conventional Worlds variant labeled "policy reform" reflects significant government action on social equity and environmental protection, along with rapid expansion of new technologies to reduce environmental impacts. Hence, these scenarios assume that rapid economic expansion can be achieved in the face of socioecological crises. The Barbarization scenarios, on the other hand, depict a future in which social conditions have deteriorated beyond the ability of markets or policy to cope. In the "breakdown" variant, economic collapse and social conflict are the outcome, whereas in the "fortress world" (used as the reference scenario), elite groups gain authoritarian control over key natural resources and populations. Conversely, the Great Transitions scenarios reflect a transformation to a sustainable society that values nature, social welfare, and equity and in which population levels have stabilized and material consumption has decreased. In the "eco-communalism" variant, socioeconomic arrangements emphasize regionalism, localism, and self-sufficiency, while the "new sustainability" paradigm is more urbanized, with socioeconomic arrangements that pursue global equity and human rights.

These global scenarios were initially quantified in 2002 using 1995 as the base year and 2050 as the "end date". The global simulations were disaggregated for 11 regions and several major sectors of the economy, highlighting several key social, environmental, and economic trends. In 2010, the scenarios were updated to reflect an additional 10 years of data (the base year was changed to 2005) and extended 50 years further into the future (to the year 2100) (http://tellus.org/programs/integratedscenarios.html). In addition to the analysis done by the Global Scenario Group, the simulations have also been applied in sustainability studies at global, regional, national, and local levels, including the UNEP Global Environment Outlook Reports, Our Common Journey by the US National Academy of Science, the World Water Council's World Water Vision, and the OECD's Environmental Outlooks.

World Business Council for Sustainable Development

In 1997, the World Business Council for Sustainable Development engaged in a collaborative project called Vision 2050 to develop a vision of the world on the path to sustainability. A set of global scenarios for the year 2050 were created based on different strategies to address the challenges of sustainable development. There are three scenarios, FROG!, GEOpolity, and Jazz.

Of the three scenarios, FROG! reflects a continued emphasis on economic growth and technological development, with sustainable development being an important but secondary concern. Economic success is assumed to differ among countries, and the implementation of global environmental standards leads developing nations to demand that developed nations

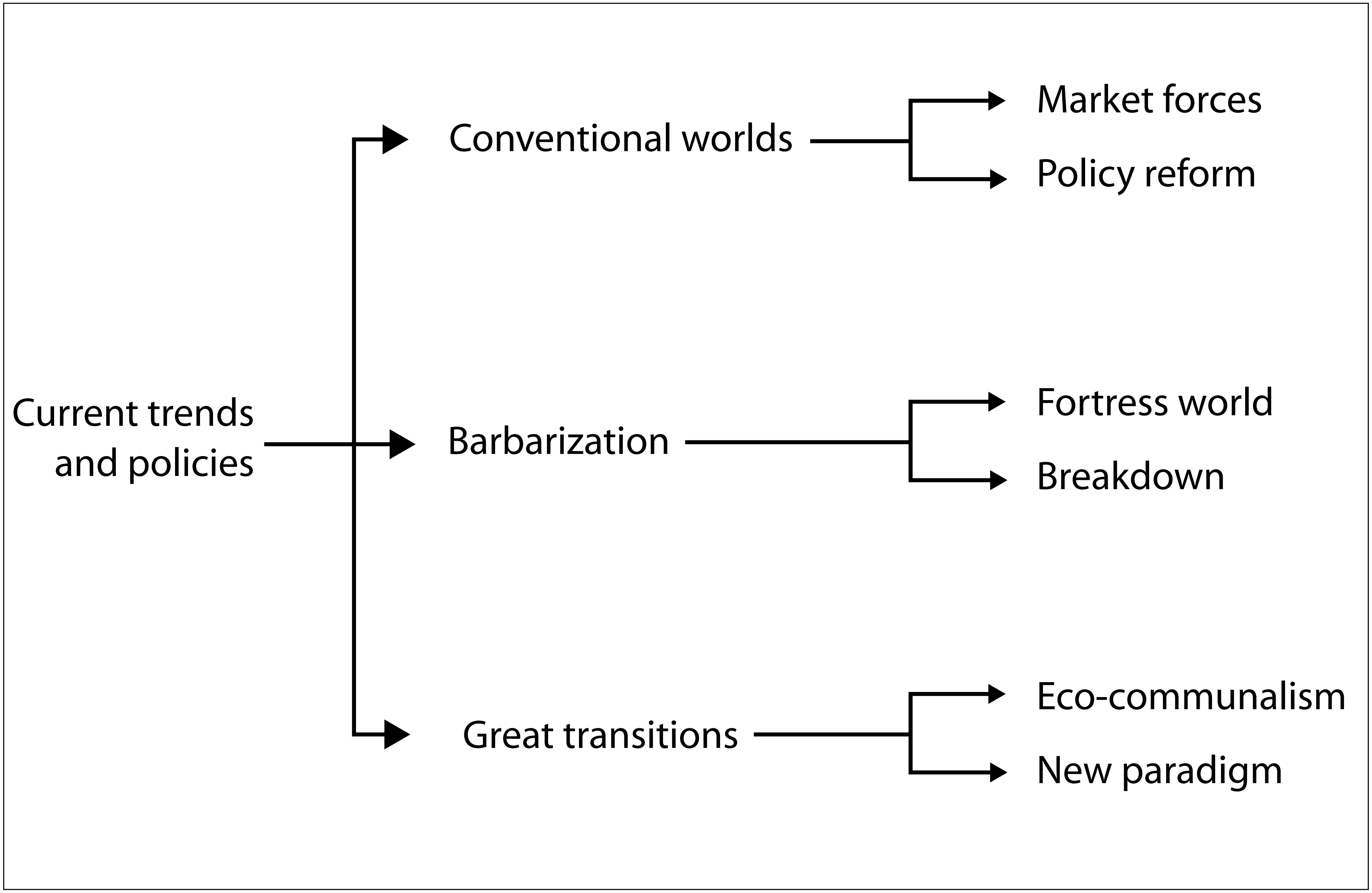

Figure A1.1. Global scenarios of economic development and population growth in the 21st century, created jointly by the Tellus Institute and the Stockholm Environment Institute. Each scenario comprises a business-as-usual baseline and a variant. Adapted from Gallopin et al. 1997.

"First Raise Our Growth!" Some developed countries provide assistance, while others act to protect their economic competitiveness. Social inequity increases and environmental health deteriorates, with the most severe predictions about climate change being realized.

In GEOpolity, social and environmental crises lead to the emergence of new global institutions that oversee economic markets to ensure they meet environmental and social standards. Governments take the lead in the institutionalization of sustainable development, while business action is lacking. Conversely, the Jazz scenario reflects novel action taken by diverse players and is facilitated by the availability of information about the social and environmental impacts of production. Self-interest leads companies to become socially and environmentally responsible.

World Energy Council

The World Energy Council (WEC) first produced scenarios of global energy futures for the World Energy Congress held in India in 1983. WEC has since released a series of publications that explore different aspects of global energy outlooks, including population growth, economic growth, technology change and transfer, energy financing and investment, energy-efficiency improvements, the natural resources base, the environment, international trade, and the cost, supply, and demand for energy (http://www.worldenergy.org/publications/). The most recent scenarios, named Lion, Giraffe, Elephant, and Leopard, were published in 2007 (WEC 2007) and are based on regional analyses using a global economic simulation model for the energy sector called POLES.

In the Lion scenario, high levels of government cooperation and integration support a strong global economy and global action on emissions and energy poverty. This scenario envisions countries in North America providing greater assistance abroad as well as investing in renewable energy and reduced consumption at home. The Giraffe scenario reflects an increased implementation of free markets, which increases global economic development, raises living standards, and decreases population growth after 2020. Financial and technological investment increases in the energy sector and governments work with private and public groups to address energy security and climate change. Private companies and government also share expertise, with increasing regional energy integration and clean energy becoming an increasing priority in North America. The Elephant scenario reflects a world with a more secure and diverse energy supply and slightly lower GHG emissions. Governments make diversified energy supplies a priority and are strongly involved in energy planning; however, there is little international cooperation on climate change. Economic growth is moderate, and globally, energy intensity decreases somewhat by 2050 in response to domestic government action. Across North America, energy infrastructure is old and private investment in energy decreases. In the Leopard scenario, economic growth is slower, emissions are higher, and there is greater uncertainty. This world reflects minimal global or regional cooperation, little government intervention, and a focus on national energy supply. Energy intensity increases in developing countries and slowly declines in developed countries, causing global energy demand to increase overall.

More recently, WEC was engaged in a new energy scenarios exercise with its members to develop an exploratory framework and a quantitative analytical assessment of government and private policy options (WEC 2010). Their intention was to develop a web-based, open-source global energy model that can be used by knowledgeable people anywhere to develop global scenarios based on regional input.

The Shell Group

Shell began developing global scenarios in 1992 to increase understanding of the global political and economic contexts, with the aim of identifying potential future challenges and increasing the ability of the organization to adapt. Scenarios developed in the 1990s focused primarily on political and economic driving forces, while scenarios developed in the 2000s also addressed social aspects of global futures. Recent scenarios were released in 2008 (Shell 2008) and are centered on how climate change will be addressed (http://www.shell.com/global/future-energy/scenarios/previous.html). The first scenario is labeled Scramble. It describes a world in 2050 where there has been minimal attention to energy efficiency until energy supplies became scarce. This scenario therefore also assumes that GHG emissions were not seriously reduced until large impacts from climatic change were already being felt. The alternative scenario called Blueprints portrays a world where economic development, energy security, and the environment have been addressed locally by putting a price on emissions. Local actions supported investment in clean energy and conservation, resulting in significant reductions in GHG emissions. The assumptions reflected in these two scenarios are that future energy demand from developing nations, particularly China and India, will exceed the growth in supply, even as energy efficiency improvements lead to reduced consumption (see Shell 2008). This would result in rising energy prices and renewables becoming increasingly competitive.

Intergovernmental Panel on Climate Change

The IPCC has developed several sets of socioeconomic scenarios to describe the most important yet most uncertain drivers of future GHG emissions. In the IPCC's initial assessment of climate change, four socioeconomic scenarios extending to 2100 (known as SA90a to SA90d) were developed, and the associated levels of GHG emissions were estimated and used to drive GCM simulations of the resulting climate change (Appendix 1 [p. 343] in Houghton et al. 1990). Consistent rates of economic development (2.3% annually in OECD countries and 3.5% in Eastern Europe and developing nations) and population growth (10.5 billion people by the second half of the 21st century) were used, while the levels of technological development and environmental control differed among scenarios. New scenarios were developed for the IPCC's Second Assessment Report (Houghton et al. 1994). Six scenarios (IS92a to IS92f) were created, which allowed assumptions for growth rates to vary for the global economy (mean of 2.3% annually) and population (11.3 billion people by the year 2100), but GHG mitigation policies were not considered.

For the Third Assessment Report, new scenarios were developed to reflect updated information on development and GHG emissions (IPCC 2001). These scenarios were based on four narrative storylines that result from the intersection of a horizontal axis that contrasts regional connectivity with global cooperation and policy, and a vertical axis that contrasts development emphasizing market liberalization with development that places growing value on the environment and equity. Nakićenović et al. (2000) describe the four storylines created by the matrix (which became the basis of the IPCC SRES families: A1, A2, B1, and B2). The A1 scenarios reflect very rapid economic growth, population growth that peaks by 2050 and then decreases, and rapid implementation of energy-efficient technologies. The A2 scenarios represent a future with continuously increasing population but with slower economic growth that is regionally divided. The B1 scenarios signify population growth similar to that in the A1 story, but with economic restructuring away from material-intensive production towards clean technology and increased provision of services and information. The B2 scenarios denote local sustainability solutions with continuously increasing population and midrange economic development. These storylines were quantified using integrated assessment models that produced some 40 scenarios, each falling within one of the four families. Climate scientists reporting to the IPCC chose six illustrative scenarios (one each from the A2, B1, and B2 families and three from the A1 family) and used these to drive GCM simulations of future climate that could result from different development pathways. Three SRES scenarios (A2, A1B, and B1) were also used for the Fourth Assessment Report. Many studies using climate projections based on the SRES have been reported in the climate change literature and they continue to be used today. Quantitative descriptions of the scenarios, their assumptions, and some associated projections of future global temperature and sea-level rise are available from the IPCC's Data Distribution Centre (http://sres.ciesin.org/final_data.html).

New scenarios were developed for the IPCC's Fifth Assessment Reports, which were completed in early 2014, using a process that is markedly different from that used in previous assessments. In the SRES process used for the IPCC's Third Assessment Reports, storylines were developed to describe possible future socioeconomic development. The major trends associated with each storyline were subsequently quantified and used to generate multiple scenarios of future GHG emissions. These GHG scenarios were then used by GCM groups to produce many different projections of future climate change. In turn, these climate projections were made available to researchers and analysts to determine the associated ecological and socioeconomic impacts of different scenarios of climate change. This sequential process led to long delays between scenario development and their use in impact assessments (Moss et al. 2010).

The IPCC's new process for scenario development started with the selection of four GHG emissions trajectories (termed Representative Concentration Pathways, or RCPs), which lead to specified levels of global warming. Warming is quantified as a net radiative forcing (measured in watts per square meter) due to all anthropogenic activities that have occurred between the preindustrial era and those projected to occur by 2100. Hence each RCP scenario is identified by the radiative forcing projected for 2100 (2.6 W m^{-2} being the lowest and 8.5 W m^{-2} the largest). The objective was to accelerate the process that leads to impact assessments and to support better analysis of mitigation options. Moss et al. (2010) suggest three main reasons why this was necessary: (1) the SRES scenarios do not consider the effect of climate policy on socioeconomic development; (2) more detailed information is needed to run modern climate models than was provided by the SRES process; and (3) scenarios are needed that enable consistency among different types of assessments. The RCP process was therefore separated into two parallel procedures: one to estimate the different climatic changes that would result from these GHG emissions and the other to determine possible alternative combinations of actions that would cause those emissions trajectories to occur. The underlying assumption was that there are multiple ways to achieve a specific GHG emission trajectory. Therefore, socioeconomic storyline development and scenarios-based research should help to identify patterns and trends among multiple factors driving GHG emissions and lead to identification of the most effective policy options (Inman 2011).

The final phase of the RCP process involved the integration of work done in the parallel phase (Moss et al. 2008). To avoid confusion and support coordinated research, the IPCC endorsed the use of a small set of storylines (Inman 2011). The development of these "shared socioeconomic pathways" then allowed for better collaboration among integrated assessment modeling and impacts, adaptation, and vulnerability research and was expected to encourage greater inclusion of the socioeconomic dimensions of research (Kriegler et al. 2010). The final draft of the IPCC Working Group 1 Fifth Assessment Report was accepted in September 2013 (IPCC 2013), with many of the more recent scientific analysis based on GCM simulations performed using the RCP scenarios. Figure 1.15 of the IPCC WG1 report (IPCC 2013) provides a comparison of the RCP scenarios with the SRES marker scenarios, expressed in radiative forcing terms.

National and Regional Scenarios

Currently, there appear to be no comprehensive Canadian scenarios of future socioeconomic conditions. Some of the global scenarios reviewed above have been downscaled to project trends in country-level variables, but it appears that only projections of future population and GDP are available for Canada. Global scenarios have also been used to project changes in specific socioeconomic variables at the global level; some of these have either been downscaled or used to infer changes in national and smaller scale indices. Many different national- and regional-scale estimates of socioeconomic trends have been projected and could be used to develop local scenarios of future development. These various scenarios and projections are briefly reviewed below and grouped according to indicators of demography, economics, natural resource use, governance and policy, and culture.

Demographic and Cultural Indicators

Projections of future global population have been carried out by several international organizations based on country-level data. The storylines used to create these scenarios reflect a variety of potential fertility rates that would have a major influence on human population growth as well as gender and age trajectories relevant to research and planning. Bengtsson et al. (2006) provided one of the first global population projections to 2100, gridded at 0.5° spatial resolution. Other than this, gridded population projections appear to be lacking (see van Vuuren et al. 2010).

The United Nations Department of Social and Economic Affairs, Population Division (http://www.un.org/esa/population/unpop.htm), provides regular estimates and projections of global population, with the most recent released in 2012, providing projections up to 2100. As described by Raftery et al. (2012), the UN population projections are arrived at deterministically using the cohort component method, which produces a single population number for a future time period based on the age and gender structure of a country's current population plus the number of births, minus the number of deaths, plus the number of immigrants, and minus the number of emigrants. This involves multiplying the number of sex–age groups living at a given time by appropriate survival ratios to determine the number of deaths, and multiplying a birth rate specific to female survivors in a corresponding age group to project the number of births (United Nations 1956). Migration is considered to be more difficult to project, as rates are often highly variable owing to their strong tie to economic conditions in both outgoing and ingoing countries as well as changing immigration policies. Therefore, immigration and emigration numbers are normally estimated separately from projections of births and deaths (United Nations 1956).

The United Nations uses different fertility rates for Canada, which equate to projected populations ranging between 33.8 million (low fertility scenario) and 74.1 million (high fertility scenario) by 2100. These population numbers only capture migration effects on population up to the base year (2012) and not future migration rates. The latest review of migration policies and historical trends was produced by the United Nations (2009). It shows that in Canada the number of international migrants has steadily increased from approximately 4.5 million in 1990 to 7.2 million in 2010, an increase in the percentage of the total population from 16.2% to 21.3%.

Additional population projections are available from international organizations like NASA's Socioeconomic Data Center, which has a gridded population of the world at 2.5 arc-minutes resolution (1° = 60 arc-minutes) (approximately 5 km) (CIESIN 2005) and the International Institute of Applied Systems Analysis, which has geospatially downscaled population projections consistent with the SRES scenarios to large regions (http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=about). The latter projections also reflect assumptions about urbanization rates (the effects of which are visible in population density maps), energy use, economic development, and other related factors.

Scenarios of future national, provincial, and territorial populations have also been produced by Statistics Canada (http://www.statcan.gc.ca/). In 2010, they published projections of population changes from the year 2009 to 2036 for the provinces and territories and up to 2061 for Canada in its entirety (http://www.statcan.gc.ca/pub/91-520-x/91-520-x2010001-eng.htm). According to these projections, Canada's population is anticipated to be somewhere between 40.1 and 47.7 million people by 2036 and between 43.0 and 63.8 million by 2061. Under these growth scenarios, the proportion of seniors (aged 65 and older) would grow to 23%–25% of the population by 2036 and to 24%–28% by 2061. As a group, the population of seniors would be between 11.9 and 15.0 million by 2061. In these scenarios, the number of seniors will exceed the number of children aged 14 or younger between 2015 and 2021. The proportion of the total population that would be of working age would decrease to about 60% (compared with 69% in 2009) in all population growth scenarios up to 2036, and then stabilize.

Projections of Canadians identifying as Aboriginal are also available from Statistics Canada (http://www.statcan.gc.ca/daily-quotidien/111207/dq111207a-eng.htm). These projections suggest that there could be between 1.7 and 2.2 million Aboriginal people in Canada by 2031, representing 4.0%–5.3% of the total population. This population would also be younger on average compared with the non-Aboriginal population, with a median age between 35 and 37 in 2031.

Various provincial governments have also made shorter term demographic projections for their regions. Readers are encouraged to explore regional websites and compare available projections with those produced by Statistics Canada. For example, the Ontario Ministry of Finance (http://www.fin.gov.on.ca/en/economy/demographics/projections/) produced a reference scenario (continuation of observed fertility rate) as well as low and high growth scenarios to make projections for the entire province up to 2036 (using 2010 as a base year). In 2009, l'Institut de la Statistique Québec (http://www.stat.gouv.qc.ca/donstat/societe/demographie/persp_poplt/index_an.htm) also released projections of provincial population up to 2056, although these were based on a variety of scenarios to envision population differences resulting from changes in both fertility and migration rates.

In 2010, Statistics Canada released a set of population projections that address the possible future ethnocultural diversity of the Canadian population (http://www.statcan.gc.ca/pub/91-551-x/91-551-x2010001-eng.htm). The projections include information about visible minority status, religious denomination, mother tongue, generation status, and place of birth for Canada's 33 census metropolitan areas in 2031. The data indicate that Canada's ethnocultural diversity would increase greatly, with a substantial majority of visible minorities living in metropolitan areas. The assumptions and scenarios used to make these projections are described in Malenfant et al. (2010).

Economic Indicators

International organizations, including the Organization for Economic Cooperation and Development (OECD) and the World Bank routinely develop a variety of projections related to the global economy and related topics that are often disaggregated to the national level. Many of these projections, however, have a short-time frame relative to the century-long projections of climate and environmental change. For example, OECD produces 2-year forecasts of key macroeconomic variables based on critical assumptions about future exchange rates, commodity prices, and macroeconomic policies. This process begins with the projection of a global outlook generated by the INTERLINK world economic model. These projections are then checked by financial and economic experts from both OECD and non-OECD countries to ensure that they are not implausible given national experience. Some of the domestic economic variables that are projected include expenditure, employment, wages, prices, GDP, foreign trade, and balance of payments (published in the Annex Tables of the Economic Outlook). The OECD also produces medium-term scenarios (7-year projection) for comparison and exploration of longer term economic development, but these are based on the assumption that economic growth eventually reaches an established level consistent with the shorter term scenarios. For a recent assessment of the accuracy of OECD projections, see Vogel et al. (2007).

Canadian organizations that make overall economic projections for Canada and various regions and sectors include the major banks (such as the Royal Bank of Canada, http://www.rbc.com/economics/index.html), as well as groups like the CD Howe Institute (http://cdhowe.org/), the Canada West Foundation (http://cwf.ca/), the Conference Board of Canada (http://www.conferenceboard.ca/topics/economics/default.aspx), and many others. Campbell and Murphy (2006) evaluated the performance of several Canadian forecasting organizations over the period 1984–2003. They compared the relative performance of individual forecasts and contrasted the accuracy of the Canadian consensus (average of forecast for four individual variables) with that of the OECD projections. They found that the predictions of the Canadian forecast industry are statistically homogenous and even found evidence to suggest that there was some clustering (i.e., the range of forecasts is not statistically significant), although they ranked the Toronto Dominion Bank (http://www.td.com/economics/index.jsp) as having the most successful forecasting performance overall (but, as always, past success is no guarantee of future performance!). The Canadian forecast consensus was found to have anticipated Canadian economic performance more accurately than the OECD projection.

It should be noted that some organizations provide free access to their forecasts and even some of their modeling tools. For example, the World Bank has developed a set of models that can be used freely to project and analyze a range of macroeconomic variables at the country level, including trade, finance, and income distribution. The Global Income Distribution Dynamic model simulates global economic growth using a CGE microsimulation framework that accounts for the macro nature of growth and integrates a microeconomic (that is, individual and household) dimension. The Global Income Distribution Dynamic recognizes 121 countries and includes 90% of global population, making it the first macro–micro global simulation model. The Global Linkage model is also a global dynamic CGE model that supports global trade policy analysis. iSimulate is a platform for performing collaborative economic simulations over the internet. It currently hosts a number of experimental World Bank economic models, including a global macroeconomic forecasting model for more than 150 countries, a model simulating terms-of-trade shocks, and a potential output model. The Maquette for Millennium Development Goals Simulations tool is a dynamic CGE model designed for country-level analysis of medium- and long-run development policies, including strategies for reducing poverty and achieving the Millennium Development Goals. The ENVISAGE model is designed to analyze a variety of issues related to the economics of climate change. These models are accessible for free at the World Bank website (http://go.worldbank.org/KOMGUHXSG0), but others are only available for a fee. For instance, the Conference Board of Canada provides a range of national, provincial, territorial, and regional economic forecasts as well as projections of economic growth in important economic sectors, including wood and paper production. They offer 5- and 20-year economic forecasts of nine key drivers of the national economy.

In 2010, a set of scenarios was released under the auspices of the Biopathways project (Palma et al. 2010), an initiative supported by the Forest Products Association of Canada, FPInnovations, the Canadian Forest Service, and several other organizations (Palma et al. 2010). These scenarios explore potential impacts on traditional forest products and new bioproducts sectors that could result from different energy, carbon, and fibre development pathways up to 2020. The impacts of these scenarios on the rate of return on capital employed in producing a range of forest products were analyzed using a biopathway model to determine the relative effects for British Columbia and Quebec. Scenario A (The World Continues its Course) reflects a return to precrisis economic activity that translates into variable viability for both traditional and novel products alike. Scenario B (Repeated Economic Meltdown) is a less optimistic economic picture that leads to an overall reduction in the profitability of most products analyzed. Scenario C (Skyrocketing Energy Prices) explores the impacts of economic recovery and high global energy consumption, which translates into declining profitability of traditional forest products and high profits for bioenergy. In scenario D (Growing Carbon Economy) carbon is traded globally while public support for environmentally friendly energy rises significantly. However, many of the forest products examined were found to be unprofitable in this scenario owing to the high price of carbon.

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APPENDIX 2

Sources of Climate Data and Climate Scenarios

The following pages list sources of climate data that should be of value in performing SFM vulnerability assessments. They cover the entire range of scales, from global scenarios obtainable from the IPCC Data Distribution Centre (now located in the UK) to the ClimateWNA package, which can be downloaded and installed on a desktop computer.

All the websites provided here were live at the date of publication, though some sites had not been recently updated.

Canadian Centre for Climate Modelling and Analysis (CCCma)

Websites: http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En (English)
http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=Fr (French)

Host agency: Environment Canada

Partners: University of Victoria

Content: Canadian GCM and RCM simulation data and online tools for visualizing these

Data sets: GCM and RCM output from current and past modelling experiments, at native temporal and spatial resolutions

Region: Canada to global

Comments: The website is the primary source of recent data from CCCma GCMs and the Canadian Regional Climate Model. Registration is required to have access to data. The publications pages document the productivity of CCCma researchers and their collaborators from university groups and other government agencies, both within Canada and abroad. Sadly, this has not been updated since 2005.

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Canadian Climate Change Scenarios Network (CCCSN)

Websites: (English) (archived) (French)	http://www.cccsn.ec.gc.ca/?page=main&lang=en http://www.cccsn.ec.gc.ca/?page=main&lang=fr
Host agency:	Environment Canada
Partners:	OURANOS and several university groups
Content:	Scenario information; raw climate data; reanalysis data; scenario data; downscaling tools; links to GCM websites. Tools for graphing and mapping scenario data.
Data sets:	Multiple GCMs; multiple emission scenarios (from IPCC Second, Third, and Fourth Assessment Reports); Canadian RCM; multimodel ensemble data; Environment Canada archives; gridded data sets.
Region:	Canada, divided into five regional nodes.
Comments:	Data can be conveniently downloaded in text format (CSV; comma-separated values), for single geographic locations. Data are available for monthly, yearly, and seasonal periods, from 1961 to 2100. Content on this site has not been updated since June 2012, although a notification that the content has been archived was last modified in July 2013 (https://www.ec.gc.ca/sc-cs/default.asp?lang=En&n=FE6B6E6B-1). The data distribution function has been superseded by PCIC.
Key reference:	A large number of publications are listed at http://www.cccsn.ec.gc.ca/?page=publication-index, but none appear to be on the topic of CCCSN itself.

Canadian Forest Service (CFS)

Websites: http://cfs.nrcan.gc.ca/projects/3/3 (English)
http://scf.rncan.gc.ca/projets/3/3?lang=fr_CA (French)

Host agency: Natural Resources Canada

Partners: Environment Canada, Australian National University (ANU)

Content: Monthly climate data extending back to 1901 interpolated from station records using ANUSPLIN (e.g., Hutchinson et al. 2009); time series of monthly climate change scenario data interpolated from selected GCMs; derived biophysical indicators, including moisture indexes (CMI; e.g., Hogg et al. 2013); web-based tools for mapping and to select data sets for download.

Data sets: Multiple GCMs; multiple emission scenarios (from IPCC Third and Fourth Assessment Reports); gridded data sets for multiple climate variables, including solar radiation, humidity, and wind speed.

Region: Canada and United States. Recent data sets from IPCC AR5 include Mexico.

Comments: Data can be requested online from Great Lakes Forestry Centre or by sending a request to D.T. Price (dprice@nrcan.gc.ca) or D.W. McKenney (dmckenne@nrcan.gc.ca). A feature at https://glfc.cfsnet.nfis.org/mapserver/cl_p/climatepoints.php?lang=e allows rapid online interpolation of many climate variables at multiple locations by uploading a file in CSV format containing a maximum of 10 000 sets of coordinates. Data are available for monthly, yearly, and seasonal periods from 1901 to 2100.

Key references:

Hogg, E.H.; Barr, A.G.; Black, T.A. 2013. A simple soil moisture index for representing multi-year drought impacts on aspen productivity in the western Canadian interior. Agric. For. Meteorol. 178–179: 173–182. doi: 10.1016/j.agrformet.2013.04.025

Hutchinson, M.F.; McKenney, D.W.; Lawrence, K.; Pedlar, J.H.; Hopkinson, R.; Milewska, E.J.; Papadopol, P. 2009. Development and testing of Canada-wide interpolated spatial models of daily minimum/maximum temperature and precipitation for 1961–2003. J. Appl. Meteorol. Climatol. 48(4): 725–741. doi: 10.1175/2008JAMC1979.1.

McKenney, D.W.; Hutchinson, M.F.; Papadopol, P.; Lawrence, K.; Pedlar, J.; Campbell, K.; Milewska, E.; Hopkinson, R.F.; Price, D.; Owen, T. 2011. Customized spatial climate models for North America. Bull. Am. Meteorol. Soc. 92(12): 1611–1622. doi: 10.1175/BAMS-D-10-3132.1.

Price, D.T.; McKenney, D.W.; Joyce, L.A.; Siltanen, R.M.; Papadopol, P.; Lawrence, K. 2011. High-resolution interpolation of climate scenarios for Canada derived from general circulation model simulations. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. Inf. Rep. NOR-X-421. Also available at: http://cfs-scf.nrcan-rncan.gc.ca/publications?id=32971.

ClimateBC/WNA

Websites:	http://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/ (downloads) http://climatemodels.forestry.ubc.ca/climatewna/ (online version)
Host agency:	The University of British Columbia, Faculty of Forestry
Partners:	University of Alberta, B.C. Ministry of Forests
Content:	Climate data and climate scenario data from all GCMs providing data for IPCC AR4, interpolated bilinearly to user-defined coordinates. Multiple locations can be set up in an input file.
Data sets:	Climate data are obtained primarily from PRISM (e.g., Daley et al. 2008) Some are also interpolated using ANUSPLIN (e.g., Hutchinson et al. 2009, the UEA Climate Research Unit, and interpolated 0.5° multiple GCMs; multiple emission scenarios (from IPCC Second, Third, and Fourth Assessment Reports).
Region:	Western provinces and territories of Canada nd the western United States, extending east to western Manitoba.
Comments:	Developed by Hamann and coworkers (2013), ClimateWNA extends earlier versions covering British Columbia (ClimateBC) and the Canadian Prairie provinces (ClimatePP). The package can be downloaded and installs on any modern personal computer running Windows. Intended primarily for mapping climate zones and examining GCM projections of future changes, data are available for yearly periods from 1901 to 2100 on monthly, seasonal, and annual time steps (or averaged over longer periods).
Key references:	Daly, C.; Halbleib, M.; Smith, J.I.; Gibson, W.P.; Doggett, M.K.; Taylor, G.H.; Curtis, J.; Pasteris, P.P. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. Int. J. Climatol. 28(15): 2013–2064. doi: 10.1002/joc.1688 Hamann, A.; Wang, T.; Spittlehouse, D.L.; Murdock, T.Q. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bull. Am. Meteorol. Soc., 94: 1307–1309. doi: 10.1175/BAMS-D-12-00145.1. Hutchinson, M.F.; McKenney, D.W.; Lawrence, K.; Pedlar, J.H.; Hopkinson, R.; Milewska, E.J.; Papadopol, P. 2009. Development and testing of Canada-wide interpolated spatial models of daily minimum/maximum temperature and precipitation for 1961–2003. J. Appl. Meteorol. Climatol. 48(4): 725–741. doi: 10.1175/2008JAMC1979.1. Mbogga, M.S.; Hamann, A.; Wang, T. 2009. Historical and projected climate data for natural resource management in western Canada. Agric. For. Meteorol. 149: 881–890. doi: 10.1111/j.1365-2664.2010.01830.x.

Wang, T.; Hamann, A.; Spittlehouse, D. 2010. ClimateWNA v4.60 – a program to generate climate normal, annual, seasonal, and monthly data for genecology and climate change studies in Western North America (WNA) region. 6 p. Available at: http://www.genetics.forestry.ubc.ca/cfcg/ClimateWNA/ClimateWNA.html. Accessed 18 March 2014.

Climate Wizard

Websites:	http://climatewizardcustom.org/ http://climatewizard.org/#
Host agency:	US Nature Conservancy
Partners:	University of Washington, University of Southern Mississippi, Climate Central, Santa Clara University
Content:	Climatologies and IPCC AR4 GCM projections (SRES GHG scenarios).
Data sets:	GCM data interpolated to 0.5° resolution global geographic grid, with US coverages at 4 km (past climatology) and 12 km (GCM projections). Models and ensemble means are limited to changes over the period 1951–2002 and projected for two 30-year time slices (2041–2070 and 2071–2100). Data sets are available as global and regional coverages in ASCII format.
Region:	United States and global
Comments:	User-friendly viewing and downloading, including subregions of the global coverages. Uses ESRI map server interface. Climate Wizard Custom provides a means of creating arbitrary polygons or uploading ESRI shapefiles to define regions of interest. Provides a Twitter feed.
Key reference:	Girvetz, E.H.; Zganjar, C.; Raber, G.T.; Maurer, E.P.; Kareiva, P.; Lawler, J.J. 2009. Applied climate-change analysis: the Climate Wizard tool. Plos One 4(12): e8320, 19 p. doi: 10.1371/journal.pone.0008320. Also available at: http://www.plosone.org/article/fetchObject.action? uri=info%3Adoi%2F10.1371%2Fjournal.pone.0008320&representation=PDF.

Data Access Integration (DAI) Portal

Websites: http://loki.qc.ec.gc.ca/DAI/DAI-e.html (English)
http://loki.qc.ec.gc.ca/DAI/DAI-f.html (French)

Host agency: Global Environmental and Climate Change Centre (GEC3)

Partners: Environment Canada, Adaptation and Impact Research Section (AIRS), Meteorological Service of Canada, Quebec branch, OURANOS, Canadian Climate Change Scenarios Network, Canadian Drought Research Initiative (http://www.drinetwork.ca/)

Content: GCM and RCM projections, including some created by OURANOS, and various downscaling tools. Data are from a limited number of relatively old models.

Data sets: Canadian CGCM2 CGCM3.1, Hadley Centre HadCM3. Canadian CRCM and French ARPEGE model data are supposedly available but were not accessible at time of writing.

Region: Global, with regional coverage of North America

Comments: Requires preregistration to gain access, but this process is automated. The web server uses OPeNDAP (http://opendap.org/support), with both THREDDS and GRADS data servers supported. Data can be generated to be displayed using Google Earth. The site has not been updated since May 2010, and the resources available reflect this.

Hectares BC

Websites:	http://www.hectaresbc.org/app/habc/HaBC.html
Host agency:	Province of British Columbia
Partners:	Biodiversity B.C., Nature Conservancy Canada, Fraser Salmon and Watersheds Program, GeoConnections Canada, Fisheries and Oceans Canada, Parks Canada
Content:	Many types of data, including administrative units, ecological zones, aquatic units, land use, protected areas, etc., as well as climate and climate change scenarios.
Data sets:	Spatial data covering B.C. in the Hectares BC database can be downloaded. There may be restrictions to access for some of these data layers.
Region:	British Columbia
Comments:	Very powerful GIS-oriented map server that allows complex queries and overlays of land-cover data sets. Designed to work best with Firefox or Google Chrome web browsers.
Key reference:	DataBC. 2013. Hectares BC quick reference guide. Gov. B. C. Minist. Labour, Citizen's Serv., Open Gov., Victoria, BC. 2 p. Available at http://www.data.gov.bc.ca/local/dbc/docs/geo/habc/20091110-Hectares_BC_both.pdf. Accessed 18 March 2014.

IPCC-DDC (Intergovernmental Panel on Climate Change Data Distribution Centre)

Websites: http://www.ipcc-data.org

Host agency: UK Department of Energy and Climate Change (also British Atmospheric Data Centre; BADC)

Partners: Academic and government research institutions worldwide. The IPCC-DDC also links to the PCMDI website.

Content: Climate data, including GHCN, NCEP, BADC, CRU, etc.; climate change scenario data from current and previous versions of most GCMs; links to GCM websites; reports that include socioeconomic scenarios (also see Appendix 3); global data sets on atmospheric chemistry, land use change, soils, agriculture, biodiversity; guidelines on using data sets.

Data sets: Multiple GCMs; multiple emission scenarios (as used in IPCC Assessment Reports), monthly time series and decadal-scale means.

Region: Global

Comments: In the past, not all data have been available even when listed. Files of monthly climate variables are generally in GRIB or compressed ASCII format. Data from more recent experiments are generally available from PCMDI. Files in GRIB or NetCDF formats will require some programming skills to unravel, though tools are available to simplify this process.

The Environmental Data Section of the IPCC-DDC (http://www.ipcc-data.org/observ/ddc_envdata.html) provides access to baseline and scenario data for a range of nonclimatic factors related to atmospheric, aquatic, and terrestrial environments. These include data on atmospheric composition (e.g., carbon dioxide, ozone), land use and land cover, sea level, and water availability and quality. Most projections are consistent with the driving factors and emissions presented in the Special Report on Emissions Scenarios (Nakićenović et al. 2000).

Key references: (IPCC) Intergovernmental Panel on Climate Change. 2014. Climate change 2013: the physical science basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Final Draft. Available at: http://www.climatechange2013.org/report/review-drafts/. Accessed 12 January 2014.

Nakićenović, N.; Alcamo, J.; Davis, G.; de Vries, B.; Fenhann, J.; Gaffin, S.; Gregory, K.; Grübler, A.; Jung, T.Y.; Kram, T.; La Rovere, E.L.; Michaelis, L.; Mori, S.; Morita, T.; Pepper, W.; Pitcher, H.; Price, L.; Raihi, K.; Roehrl, A.; Rogner, H.-H.; Sankovski, A.; Schlesinger, M.; Shukla, P.; Smith, S.; Swart, R.; van Rooijen, S.; Victor, N.; Dadi, Z. 2000. Special report on emissions scenarios. A special report of Working Group 3 of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. 599 p. Also available at: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0.

North American Regional Climate Change Assessment Program (NARCCA)

Websites: http://www.narccap.ucar.edu/

Host agency: US National Center for Atmospheric Research (NCAR)

Partners: OURANOS and several US agencies

Content: High-resolution climate projection data, created primarily using regional climate models (RCM)s, nested within GCMs. Time-slice experiments are commonly carried out, but some continuous time series data are being produced.

Data sets: Large archive of high-resolution data, stored using netCDF (see http://www.unidata.ucar.edu/software/netcdf/), but can be downloaded in ASCII format.

Region: Canada, United States, and northern Mexico.

Comments: This is the most comprehensive archive of freely available RCM data covering North America.

Key reference: Mearns, L.O.; Gutowski, W.J.; Jones, R.; Leung, L.-Y.; McGinnis, S.; Nunes, A.M.B.; Qian, Y. 2009. A regional climate change assessment program for North America. EOS 90(36): 311–312. doi: 10.1029/2009EO360002.

Ontario Ministry of Natural Resources (OMNR)

Websites: http://www.mnr.gov.on.ca/en/Business/ClimateChange/2ColumnSubPage/STDPROD_090054.html

Host agency: OMNR

Partners: OMNR Science and Information Resources Division and Provincial Geomatics Service Centre, Canadian Forest Service, Environment Canada

Content: Online viewer for interpolated maps of present-day climate and future climate scenarios for Ontario, for 30-year periods (1971–2000, 2011–2040, 2041–2070, 2071–2100) in summer and winter. Future scenarios are limited to those produced by the Canadian Coupled Global Climate Model Version 2 (CGCM2) forced by the SRES A2 and B2 emissions scenarios.

Data sets: Not available

Region: Ontario

Comments: OMNR produces a range of reports and other information useful for impact analysis and development of adaptation strategies that are focused on the province of Ontario, but much of the content is applicable over a wider region.

Key reference: Colombo, S.J.; McKenney, D.W.; Lawrence, K.M.; Gray, P.A. 2007. Climate change projections for Ontario: practical information for policymakers and planners. Ont. Minist. Nat. Resour. Appl. Res. Dev. Branch, Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-05. Also available at http://www.climateontario.ca/MNR_Publications/276923.pdf.

OURANOS (Consortium on Regional Climatology and Adaptation to Climate Change)

Websites: http://www.ouranos.ca/en/ (English)
http://www.ouranos.ca/fr/ (French)
http://www.ouranos.ca/en/scientific-program/scientific-program.php

Host agency: Private nonprofit organization with multiple funding sources

Partners: Many within Quebec and others across Canada. OURANOS works closely with the Canadian Regional Climate Model (CRCM) development group at Université de Québec à Montréal (UQAM) and Environment Canada's Canadian Centre for Climate Modelling and Analysis (CCCma).

Content: Information and expertise. OURANOS coordinates assessments of climate change impacts and vulnerability in Quebec and contributes to the development of adaptation strategies for all sectors, including forestry.

Data sets: None available for public download. However, some older data should be available from the DAI portal (http://loki.qc.ec.gc.ca/DAI/DAI-e.html) or from CCCma (http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En).

Region: Canada (with focus on Quebec)

Comments: Data sets are available only on request and as part of collaborative projects. OURANOS scientists also operate the Canadian Regional Climate Model (CRCM, http://www.ouranos.ca/fr/programmation-scientifique/science-du-climat/simulations-climatiques/MRCC/eng/crcm.html#ref) in support of work on impacts and adaptation.

Key reference: (OURANOS) Consortium on Regional Climatology and Adaptation to Climate Change. 2012. Annual Report 2011–2012. OURANOS, Montreal, QC. 26 p. Available at: http://www.ouranos.ca/en/pdf/AROuranos2011-2012.pdf. Accessed 18 March 2014.

Pacific Climate Impacts Consortium (PCIC)

Websites: http://www.pacificclimate.org/

Host agency: University of Victoria, funded mainly by the B.C. provincial government.

Partners: B.C. government agencies; Environment Canada

Content: Information; raw climate data; reanalysis data; scenario data; downscaling tools; links to GCM websites. Tools for graphing and mapping scenario data (including ClimateWNA).

Data sets: Multiple GCMs; multiple emission scenarios (from IPCC Second, Third, and Fourth Assessment Reports); Canadian RCM; multimodel ensemble data; Environment Canada archives; gridded data sets.

Region: Western North America, particularly British Columbia.

Comments: PCIC was formerly known as the Canadian Institute for Climate Studies (which exists as an unmaintained website at http://www.cics.uvic.ca/scenarios/). Data sets are generally available upon request to PCIC and can be conveniently downloaded in text format (CSV), for single geographic locations. Data are available for monthly, yearly, and seasonal periods from 1961 to 2100.

Key reference: Murdock, T.Q.; Spittlehouse, D.L. 2011. Selecting and using climate change scenarios for British Columbia. Univ. Victoria, Victoria, BC. 39 p. Available at: http://www.pacificclimate.org/sites/default/files/publications/Murdock.ScenariosGuidance.Dec2011.pdf. Accessed 18 March 2014.

Program for Climate Model Diagnosis and Inter-comparison (PCMDI)

Websites: http://cmip-pcmdi.llnl.gov/cmip5/

Host agency: Lawrence Livermore National Laboratory (LLNL); World Climate Research Program (WCRP)

Partners: Several US national laboratories; climate modeling groups worldwide

Content: GCM climate scenario data; links to GCM websites; data analysis tools, including routines to read and write netCDF files (see http://www.unidata.ucar.edu/software/netcdf/).

Data sets: The primary source for GCM output. PCMDI hosts the archive of data used in IPCC Assessment Reports, including the Coupled Model Intercomparison Projects, Phase 3 (CMIP3) and Phase 5 (CMIP5) (see http://www-pcmdi.llnl.gov/ipcc/info_for_analysts.php#getting_started and http://cmip-pcmdi.llnl.gov/cmip5/design_overview.html?submenuheader=1).

Region: Global. Some regional data sets may also be available.

Comments: A key source of current-generation GCM projections of future climate, PCMDI was established in 1989 at LLNL (California) to develop methods and tools to compare GCMs. Became the host for model intercomparison experiments after request from WCRP in 2006. PCMDI facilitates access to GCM simulations by other researchers who contribute to the IPCC Assessment Report process. GCM monthly outputs are downloadable in netCDF format, for many variables, subject to the discretion of the contributing research group.

Key references: Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93(4): 485–498. doi:10.1175/BAMS-D-11-00094.1.

(UCAR) University Corporation for Atmospheric Research. 2014. NetCDF documentation. Available at: http://www.unidata.ucar.edu/software/netcdf/docs/index-413.html. Accessed 18 March 2014.

APPENDIX 3

Review of Forest Models

Two broad categories of models can be used to inform natural asset decision making, namely statistical and process models. Statistical models generally rely on simple or complex empirical relationships between driving variables and the predicted outputs. Process models use mathematics to represent the underlying mechanisms that link the inputs (forcing conditions) to the outputs (simulated responses), with the objective of improving agreement with observed data across a wider range of environmental conditions. Statistical models are typically calibrated to capture the observed relationships, but can fail when applied to new sets of conditions. Process models are less easily calibrated, but more likely to behave realistically when applied outside the range for which they were developed. Two important caveats here are that (1) most process models still use some level of empiricism in defining the basic mechanisms upon which they are built and (2) the greater complexity found in process models does not necessarily make them more accurate.

Statistical Models

Statistical models are well exemplified by forest growth and yield models that have been widely used in forest science and management. The strength in growth and yield models comes from the close relationship between empirical data taken from many sample plots in representative stands and the similar stands to which they are applied. The weakness is that while these relationships may hold for particular species growing on particular sites in the location where the model was developed, they are often unsuitable for other species or other site types in other regions. In particular, if average site conditions change, as they would with a changing climate, then such models can be expected to fail.

Nevertheless, such models can have a role in assessing climate change impacts. Firstly, they are extremely useful as baseline estimates when developing and validating other climate-sensitive models using historical data. Secondly, significant effort is being invested in developing climate-sensitive variants of traditional growth and yield models, often by using the results from process models to create "climate modifiers" that can be applied to the yield equations. The latter approach might be validated by observing effects of differences in latitude and elevation on climate and stand yields, and treating these as analogs for the effects of climate warming.

Climate envelope models (CEM) are a second class of statistical model that are being used extensively to project potential changes in the distribution of individual tree species resulting from shifts in climatic zones (e.g., see review of CEMs in Johnston et al. 2010). The general approach is to correlate present-day spatial distributions to the climate zones they occupy, and then attempt to predict how those distributions may change with different scenarios of future climate. CEMs do not simulate the mechanisms by which trees and other organisms might actually arrive at the future climate zones, although some modifications attempt to account for major constraints such as geographic barriers and seed dispersal rates (e.g., Iverson et al. 2004, 2008). Actual colonization may also be prevented by the absence of suitable soils, for example, at high elevations or high latitudes, but it is relatively easy to exclude such areas from model projections. The information provided by CEMs can be useful when considering adaptation strategies, such as assisted migration opportunities and options (see Ste.-Marie et al. 2011).

A major limitation in the use of CEMs is that most tree species would not be able to migrate naturally to keep up with the rates at which climate zones are projected to change in Canada, under even the most benign climate scenarios. Conversely, CEMs should be particularly useful at projecting where species may be expected to disappear if no adaptive management is applied and hence can provide important information for developing conservation strategies. For example, McKenney et al. (2007) used a CEM to project future distributions of the climate zones of 130 forest tree species in the United

States and Canada, finding that Canada would provide appropriate climates for many more species by 2100, mainly in the east, while the southern United States would lose many species present there today. The more extreme emissions scenario, SRES A2, caused climate envelopes to shift further north and decrease in area compared with those resulting from the more moderate B2 scenario.

Process Models

In contrast to statistical models, ecological process models use mathematical representations of the processes that shape ecosystem responses to changes in environmental factors. For example, annual stand-level productivity could be estimated in several distinct steps. First, the instantaneous effects of varying sunlight and atmospheric CO_2 concentration on photosynthesis and photorespiration of representative leaves can be simulated using biochemical equations with corrections applied for the effects of air temperature, nutrient availability, and plant water stress. Second, canopy total gross photosynthesis would be estimated by integrating the leaf-level estimates, say at hourly time intervals, accounting for canopy leaf area and orientation (geometric factors that influence the amount of sunlight absorbed as explicit functions of time of day and year and site latitude). Third, maintenance respiration of leaf, wood, and fine-root biomass would be estimated as different functions of temperature and then deducted to estimate hourly net primary production (NPP). Repeating these steps for each hour of each day provides estimates of daily and annual NPP. From here, NPP could be allocated to leaves, fine roots, branches, and stem wood. Some fraction of these would be lost as litter fall and tree mortality. Repeating these calculations for multiple years would result in a process-based representation of stem-wood biomass accumulation over the life of a stand. Dividing these data by an appropriate value for wood density would allow direct comparison to stand yield curves. Because the model accounts for effects of air and soil temperature, water stress, and sensitivity to CO_2 concentration, it would be considered climate sensitive and could be used to project the effects of climatic change on stand productivity.

Many forms of ecological process model have been created in recent decades. They vary considerably in the amount of detail allocated to distinct processes (or may even leave some processes out completely), generally to reflect the purpose of the model and (or) the information available to test it. A workshop coordinated by the Western Wildlands Environmental Threat Assessment Center of the US Forest Service was reported by Robinson et al. (2008). The major objective was to assess the value of different classes of climate-sensitive vegetation models for making forest management decisions in a changing climate. Of five distinct types of model reviewed, four could be considered process-based, with climate envelope models, discussed previously, being the fifth. Only a brief summary will be given here (for further information, see Robinson et al. 2008).

Forest “gap” or “patch” models were first created 40 years ago (Botkin et al. 1972), but some variants are still being developed today (e.g., Bugmann et al. 2001; Canham et al. 2004; Shuman et al. 2011). They simulate the processes of establishment, growth, and mortality, the latter leaving gaps in the canopy that can be occupied by competing species. Each tree species is parameterized to determine its ecophysiological responses to the limitations imposed by climate and soils. Trees then compete for light, water, and nutrients, on 100 or more replicate “forest patches”, typically plots of 0.1 ha or less, driven by the same daily or monthly climate data, over simulated periods of decades to centuries. Successional events, such as seedling establishment, tree death, and fires, are generated using pseudorandom numbers, so that no two patches experience the exact same stand development history. The mean values from all patches are used for diagnostic output. Although more mechanistic than statistical models, the representations of physiology in many gap models are traditionally relatively simple, requiring a few easily obtained parameters. More complex versions have been developed in recent years that take the gap model philosophy into new areas, including landscape models and dynamic vegetation models (DVM). A major strength of traditional gap models has been their capacity to simulate stand characteristics using forestry indicators, such as height and basal area, which can be compared to stand-level measurements. They are also relatively easy for nonspecialists to use at specific locations when suitable climate data (e.g. from local station records) and soils data can be obtained.

Landscape models, such as LANDIS (e.g., Mladenoff 2004; Scheller 2013; see also http://www.landis-ii.org) are relatively high-resolution stand-level simulators similar to gap models, but operate on polygons or grids covering extensive areas rather than single point locations. They are often used for operational decision making, for example, to assess effects of disturbances, particularly fire, as it spreads across a landscape to create a dynamic patchwork of stands of varying ages. Simulations are therefore usually tied to real landscapes such as forest management areas and often used to project changes in vegetation resulting from the interactions of natural stand development and disturbance events with possible management interventions. Input data typically include soils maps and spatially interpolated climatology. Keane et al. (2008) report that landscape models can be very useful for management applications, such as planning fuel management to limit the spread of wildfires. Landscape models are generally complex and often difficult to parameterize, so may not be easily used for impact assessments unless an appropriately experienced research group is involved. For example, the SEM-LAND model developed by Li and coworkers has been used to simulate forest landscape dynamics for a 1000 km^2 region in central Saskatchewan forced by a 2×CO_2 climate change scenario (Li et al. 2000). This model was subsequently enhanced to include simulation of fire management options (Li et al. 2005) and to investigate effects of fire and harvesting on landscape carbon dynamics (Li et al. 2006).

Biogeochemistry (BGC) models generally aim to simulate the detailed processes involved in the cycling of nitrogen and other nutrients within soil–plant ecosystems and their importance as controls on vegetation productivity as well as responses to climatic variations and climate change. Scholes et al. (1998) suggested that BGC models may be more robust for projecting long-term changes in forest productivity and carbon cycling due to climate change, because these models account for the key ecological processes that will change as the ecosystem itself changes. For example, changes in canopy leaf area and species composition will alter the amount of energy absorbed and fixed in photosynthesis and released through evapotranspiration, while changes in litter production and decomposition will affect nutrient cycling positively or negatively. The CENTURY model of Parton et al. (2001) is a classic example. Although BGC models are generally designed to be applied at continental to global scales, CENTURY (or its newer daily version, DAYCENT) has been applied to individual sites or using grids similar to those used for landscape simulators. BGC models typically capture soil–plant–atmosphere exchanges in more physical and physiological detail than gap models or landscape simulators, and some may capture vegetation dynamics, blurring the differences between BGC models and true DVMs, but disturbances are generally represented simplistically, and successional processes and competition among species are typically not captured. Like landscape simulators, BGC models generally require skilled modelers to run them. Neilson and coworkers incorporated CENTURY to capture soil processes in their MC1 model, using it to project forest vegetation changes at continental scales, including Canada (e.g., Lenihan and Neilson 1995). Peng et al. (1998) and Price et al. (1999) used the FORSKA gap model of Prentice et al. (1993) and CENTURY to provide greater insight into the sensitivity of central Canadian boreal forest ecosystems to climate change than was possible using each model separately.

DVMs attempt to capture all processes contributing to the presence, composition, and productivity of different vegetation biomes at continental to global scales. These models are related to forest gap models but substitute plant functional types for individual species, to project vegetation changes at the scale of entire ecozones rather than for individual stands. However, some current-generation DVMs, notably LPJ-GUESS of Smith et al. (2010), have strong similarities to traditional gap models when simulating stand-level dynamics. To date, DVMs have not been applied widely to Canada. Lenihan and Neilson (1995) carried out one study using the MC1 model (Bachelet et al. 2001). Price and Scott (2006) led a three-way comparison of MC1 with the SDGVM model of Woodward et al. (1995, 1998) and the IBIS model of Foley et al. (1996) applied to North

America, which showed disturbing differences among the models. Perhaps because of their complexity and general application at large scales, DVMs are not readily accessible to nonexperts and their results should be treated with caution.

Literature Cited

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