Review

Forest Management in a Climate Change Era: Options for Planning

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ABSTRACT

Changes in the world's climate may alter the state of forests across broad areas, through changes in tree species composition, tree productivity rates, and natural disturbance regimes. These potential changes may also have a cascading effect on associated environmental services, such as water yield, wildlife habitat composition, and biodiversity. The location, extent, and magnitude of potential changes to the climate will vary according to current regional climatic conditions. For example, RAVINDRANATH *et al.* (2006) suggest that some areas of India will become wetter and warmer under one 100-year climate change scenario. This paper examines the issues facing forest planners in an era of climate change, and illustrates the challenges and opportunities for assessing climate change scenarios in forest planning efforts. For example, accounting for tree species physiology in forest planning would allow analysts to recognize that some tree species may be less able to adapt to changing conditions. And, adding socio-economic change projections (development and recreational opportunities) to the analysis of policies will further help one understand the potential impact of climate on biodiversity. These and other additional aspects of quantitative forest planning will enable land managers and decision-makers to think through the vulnerability of forests to changes in temperature, precipitation, and wind speed. In addition, forest plans may need to consider actions that will reduce forest fragmentation, conserve biologically important resources, and reduce the vulnerability of forests to the risks presented along with an assessment of traditional forestry concerns (sustainability of timber production, sustainability of multiple uses, and sustainability of ecosystems). Thus there seems to be a need to assess broad-scale forest management scenarios that minimize adverse impacts and vulnerability to the uncertainties associated with insect, disease, drought, windthrow, and wildfire. This type of planning process would need to account for changes in climatic variables and associated changes in disturbance regimes, and recognize that some forests may be more vulnerable during the adjustment period.

Keywords: forest planning, carbon sequestration, natural disturbances, growth and yield, insect and disease

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INTRODUCTION

Over a quarter-century ago WILSON (1981) suggested that the consequences of global warming would be uncertain, but the potential for severe impacts would be significant. Increasing temperatures may lead to regionally-altered wind and rainfall

patterns, which could result in shifts of land suitable for agricultural and forestry purposes. WILSON (1981) also suggested that planning and decision-making needed to be proactive to ensure a sustainable lifestyle for the ever-growing human population, yet he recognized that these issues are generally avoided in management planning ("managers are managing .... and planners are planning"). Changes to the earth's climate may alter both the environment in which trees grow, and the subsequent growth of forests (LINDNER *et al.*, 1997). As a result, DYER (1994), among others, encouraged land-use planners to incorporate climate warming considerations into long-range planning efforts. A large number of approaches have been suggested for accommodating the development of sustainable forest plans, and given advances in computer technology, computer software, and data acquisition and management

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processes, planning efforts can become quite a complex endeavor (MITCHELL *et al.*, 2004). At the extreme, planning models could be considered multi-objective and dynamic, with feedback mechanisms and system interactions that address a fuzzy decision environment. As INNES *et al.*, (2009) suggest, management planning will evolve as new stresses and threats affect forestlands, and new management strategies will likely be developed to take advantage of the opportunities posed by a changing climate. However most current forest plans are developed in a rather deterministic manner (HUANG *et al.*, 1998).

The level of sensitivity of forest management goals to potential climate changes will be a function of the current and future forest landscape pattern, the temporal and spatial impacts of climate changes, and the specific effects of these changes on forest trees (BLATE *et al.*, 2009). The problem in forest planning with regard to potential changes in the climate is best described by BINKLEY and VAN KOOTEN (1994), who suggest that three systems need to be integrated: climate, terrestrial, and forest sector. Current estimates of climate change suggest that the changes may be too rapid for some forests to naturally maintain or adjust their structure, function, and composition (Bosworth *et al.*, 2008), thus some sort of management intervention may be necessary. The probable effects include increased warming at higher latitudes of the northern hemisphere, and decreased precipitation and soil moisture patterns in the middle latitudes, along with an increased frequency of dry years (TURNER and ROMME, 1994). These conditions can lead to changes in the frequency of natural disturbances, since wildfire (for example) potential is related to fuel moisture, precipitation, and humidity conditions. The increase in vulnerability of forests world-wide is therefore related to the spatial distribution of forested areas, projections of spring and summer temperatures, and projections of water availability (WESTERLING *et al.*, 2006).

Revenue generated from planned timber harvests can potentially support the forest management activities necessary to address alterations in the timing, frequency, and intensity of natural disturbances due to climate changes (GÄRTNER *et al.*, 2008). As a result, planners may be asked to take historical and projected changes in the climate into consideration when developing long-term forest management plans (BOSWORTH *et al.*, 2008). For this review, a comprehensive literature search was performed to understand the current opinion of experts around the world as it relates to the actions necessary for land management planners to account for, and develop management responses to, potential changes in the world's climate. This review is focused not on the evolving philosophies of sustainable forest management or adaptive management, which guide many of the strategies that have been proposed to address potential changes to the climate, but on the specific actions planners can take to address the concerns of an evolving set of needs of land managers and decision-makers.

DISCUSSION

The literature concerning the potential impacts of changes in climate on forest resources is extensive. Most of the research centers on the use of general circulation models and their predictions of climate changes and the resulting vegetation patterns. This paper was designed to categorize the opinions of researchers, along with their recommendations, into suitable themes that relate directly to forest management planning processes. As a result, the discussion that follows concentrates on shifts in land use, changes in vegetation patterns, natural disturbances, growth and yield modeling, the scale of planning, carbon sequestration, invasive species management, and the acknowledgement of uncertainty in planning models. After a brief description of the potential issues that may arise for each of these topics, some specific issues regarding the recognition of these issues in forest plans are highlighted. In contrast to much of the published literature, which generally promotes changes in management philosophy given projected changes in the climate, this discussion identifies the challenges facing planners to address the concerns of land managers and decision-makers who desire to see potential changes to the climate acknowledged in forest plans.

Shifts in Land Use

Land management planning generally begins with an assessment of land classes and their suitability for accommodating a wide variety of forest-based uses (BETTINGER *et al.*, 2009). These determinations are usually made once, at the beginning of the planning effort, and are usually considered fixed throughout the temporal extent of the time horizon under consideration. However, under many climate change scenarios, agricultural and forest uses of the land will likely shift as areas become more (or less) capable of producing crops in an economically efficient manner. Significant changes in the prices for agricultural and forest products could also influence land use distribution (HODGES *et al.*, 1992). And, changes in markets, trade, prices, and non-timber resource values may further affect land tenure in some areas of the world undergoing climate changes (BINKLEY and VAN KOOTEN, 1994). Although policies differ on private and public lands, there is a need to assess the tree species used for widespread planting efforts in reaction to climate change, and to prohibit the distribution of exotic tree and plant species that may cause problems in the future (THORPE *et al.*, 2006). Unfortunately, the gridlock created by human development of land, as expressed through land use changes, forest fragmentation, and public desires, has never before affected the natural evolution of tree species range distributions (BOSWORTH *et al.*, 2008). In addition to changes in suitable land uses, forest roads may need to be evaluated and perhaps re-designed to withstand changes in rainfall intensity and erosion events (BLATE *et al.*, 2009). As a result, the following items are suggested for consideration in the development of

forest plans.

- For long-range planning efforts there seems to be a need to develop evolving land classification and use projections that take into account changes in climatic variables and their effect on natural forest distribution and composition.
- Similarly, human developmental pressures should be projected and incorporated into forest plans to assess management options and resource vulnerability.
- Forest road systems need to be assessed for their ability to provide access over time to resources of interest, and for their contribution to resource degradation in response to shifts in precipitation patterns.

Shifts in Natural Vegetation Patterns

Predictions regarding shifts in the natural range of vegetation are typically based on models that were developed from correlations between the conditions of sites that were occupied by certain tree species, and the conditions of sites that were not, and these projections thus assume that climate is the major factor in determining future natural ranges of vegetation (CARMEL and FLATHER, 2006). As a result, the potential impacts of changes in the climate on forest distribution and forest health would obviously affect forest management decisions, and therefore adversely affect some (if not all) forest-based economies (HODGES *et al.*, 1992). Historically, plant and animal species have both shifted their natural ranges due to climatic changes; the retreat of glaciers and subsequent colonization by tree species is but one example of new patterns of vegetation were created after changes in the climate (BOSWORTH *et al.*, 2008). Water stress is partly responsible for vegetation pattern shifts, although local temperatures and nutrient availability are factors as well (MARTIN, 1996). Simply put, potential changes to the climate may affect the suitability of land to support vegetation (HUANG *et al.*, 1998). The effect of these changes will likely affect natural disturbance frequency, intensity, and duration as well. TURNER and ROMME (1994) proposed that the vegetation that naturally regenerates in areas of large and severe wildfires may gradually be different in composition than the plant communities that were present before fires. However, some have suggested that the current pattern of vegetation on the landscape could provide a useful indication of future vegetative and landscape mosaic trends in the event of a changes in natural disturbances under a changing climate (TURNER and ROMME, 1994).

The dispersal mechanisms of trees and the interactions among tree species need to be taken into account with changes in the climate (DAVIS *et al.*, 1998). Therefore, changing climate conditions may represent a threat to biodiversity, as tree species may be required to disperse through fragmented landscapes in order to keep pace with conditions favorable to their existence (PEARSON and DAWSON, 2005). Further, the natural range limits of a number of tree species may shift dramati-

cally under a warming climate scenario, and therefore the ability of tree species to naturally migrate is a concern (DYER, 1994). Tree species with small natural geographical ranges may be the most vulnerable (SCHWARTZ *et al.*, 2006), and under the worst-case scenario that LINDNER *et al.* (1997) examined, none of the forest tree species that are currently present in one region of the world (Germany) could thrive in certain areas of the landscape.

Managing for forest complexity is likely to result in a landscape with greater resilience toward changes in climate (CROW, 2008). However, additional information on the potential shifts in vegetative patterns as a result of climate change is needed, since some (e.g., CLARK, 1998) have proposed that some plant species may be able to migrate naturally at rates faster than those predicted from average dispersal distances. The value of management actions aimed at adapting to climate change should be considered, since attempting to maintain the existing ecosystem components may not be adequate, thus intensive management actions that are designed to deliberately shift the range of tree species to newly-formed suitable habitat may be necessary (THORPE *et al.*, 2006). Planning for natural corridors to facilitate tree species migration has also been suggested (BLATE *et al.*, 2009), however, natural corridors that are designed for migration of plants through seed dispersal processes may not be effective, since migration may not keep pace with the projected change in climate (PEARSON and DAWSON, 2005). Others suggest that a landscape composed of many small patches within a few larger patches will best serve to connect various ecosystem functions and facilitate the flow of materials and organisms across the landscape (CROW, 2008).

The argument for these assessments is centered on our attempt to assist the evolution of forested environments toward a new equilibrium that can once again thrive without a continued series of management actions (THORPE *et al.*, 2006). Further, since successional dynamics of natural areas will likely change (BLATE *et al.*, 2009), there will be a need to organize and carefully consider the potential impact of these dynamics on planning processes that include state-transition modeling components, since management actions that would assist the transition and adaptation of forests would seem appropriate under some circumstances (MILLAR *et al.*, 2007). Artificial regeneration of tree species on the edges of, or outside, their natural range may be important in assisting with the migration process (NITSCHKE and INNES, 2008), thus as noted earlier, flexibility in the land classification and allocation processes would seem necessary to account for these types of transitions across the landscape. However, trees need to be of proper genetic characteristics for the climate in which they are established (CROOKSTON *et al.*, 2008). In sum, in response to shifts in the natural range of vegetation may require planners to:

- Examine alternatives for managing forest resources in a manner (spatially and temporally) that may facilitate the migration of tree species (naturally regenerated and planted)

and toward conditions to which they might become adapted (PEARSON and DAWSON, 2005).

- Plan for natural corridors for tree species migration (BLATE *et al.*, 2009).
- Develop alternative transitional pathways for forest management regimes that take into account the notion that trees will be stressed along the boundaries of their shifting natural ranges.

Natural Disturbances and Disturbance Processes

Changes in climate may have an effect on the frequency, intensity, and range of disturbance events such as wildfires, insect outbreaks, and the spread of disease (HUANG *et al.*, 1998; YANCHUK and ALLARD, 2009). A number of research studies suggest that increases in the probability of catastrophic losses from these events are likely. BLATE *et al.* (2009) also suggest that there will be a shift in hydrologic processes due to changes in precipitation timing and intensity, and due to the threat of drought in some areas. Therefore, changes in climate may also affect water resources that depend on precipitation levels, and hence affect water yields (SUN *et al.*, 2009; WANG *et al.*, 2008). As a result, if future climatic conditions are assumed to be different than past conditions, natural disturbance rates would likely change, and the condition of the landscape and capability of forests to produce desired outcomes will then likely change. In response to these potential effects, planners could adjust disturbance parameters of interest (frequency, intensity, size, and duration of disturbances recognized) over the time horizon of a forest plan to reflect the potential changes (CAMPBELL and DEWHURST, 2007).

Forest growing seasons will likely be affected under current scenarios as they generally lengthen, and hotter, drier conditions may result in increases in insect and disease mortality rates (BOSWORTH *et al.*, 2008; BLATE *et al.*, 2009). Therefore, potential changes in the climate will likely have an impact on the frequency, intensity, and scope of insect and disease outbreaks. For example, with increased temperatures in higher latitudes, SIEBEN *et al.* (1997) suggest that there will be sufficient growing season heat to facilitate the expansion of the range of the white pine weevil (*Pissodes strobi*) northward and upward in elevation. Commercial thinning is widely seen as a way to control insect outbreaks through adjustments in stand density and alterations of the growing environment, however thinning without fuel management actions may be counter-productive because fire risk may increase given additional fuel loads on the ground. This issue is complex, since key wildlife habitat characteristics, such as snags and down logs, may also be viewed as fuel components, and may need to be maintained on the landscape in order to conserve habitat quality for plant and animal species that require these components (NITSCHKE and INNES, 2008).

The changes in the frequency, intensity, and scope of wildfires will vary according to the spatial juxtaposition of

forest resources in relation to potential changes to precipitation and air temperature patterns. In western Canada for example, fire danger is projected to increase given associated increases in summer temperatures (KADONAGA, 1997). Altered fire regimes have already been detected for a number of areas in North America, with human-induced climate change is suggested as one of the causes (GILLET *et al.*, 2004; BLATE *et al.*, 2009). In planning efforts, HARTLEY and MARSHALL (1997) developed an iterative updating procedure where for each decade within a forest plan, climate conditions were predicted, wildfire and natural mortality were assumed based on probabilities of these occurring, and alternative regeneration pathways were developed for disturbed areas. As noted earlier in relation to insect and disease concerns, one adaptation option for restoring and enhancing forests is to reduce fuel loads, and increase the use of prescribed fire (BLATE *et al.*, 2009). Low-severity prescribed fire has been shown to be effective in reducing the risk high-severity wildfires, drought susceptibility, and insect and disease outbreaks (BLATE *et al.*, 2009). In this sense, prescribed fire can be used to enhance the resilience of a forested area. Unfortunately, fuels reduction treatments act to reduce carbon stocks in forests, although some of the captured woody biomass may sequester carbon in the resulting forest products. However, forest fuel management treatments can also be considered as a way to mitigate the potential emission of carbon into the atmosphere through wildfire (BOSWORTH *et al.*, 2008).

Planning processes that recognize relationships between forests and water yield should also consider the uncertainties in water supplies that may be encountered under a changing climate, particularly in areas with growing human populations that are dependent on natural sources of water for general public use (SUN *et al.*, 2008). BETTINGER *et al.* (2007) described three general processes of increasing complexity that planners might use to integrate water yield concerns into forest plans, from the general use of deterministic water yield coefficients to the sophisticated integration of complex water yield models and forest planning processes. In response to each of these concerns, planners should consider the following:

- Incorporating into planning efforts models that take into account the frequency, intensity, size, and duration of natural disturbances.
- Recognizing that alternative forest management prescriptions may be necessary to control fuel loads and to provide environmental services that result in habitat characteristics suitable for forest-dwelling wildlife.
- Understanding and recognizing through management regimes the interaction between fuels management treatments (which can act to mitigate the emission of carbon into the atmosphere) and prescribed fire treatments (which can act to emit carbon into the atmosphere), and how these can be used together to reduce the impacts of wildfire, insect, and disease issues that may arise with changes to the climate.

- Incorporating more closely water yield models with forest planning efforts.

Growth and Yield Modeling

The suggested changes in the climate (namely precipitation and temperature), if realized, will affect the quality of forest-growing sites, and with proposed shifts northward in the range of some tree species, yields of wood products in the southern-most areas are projected to decline (HODGES *et al.*, 1992). The projection of forest inventory characteristics through time, assuming changes in climate, will require that relationships be developed between the forest inventory and climate variables such as temperature and precipitation (HARTLEY and MARSHALL, 1997). Therefore, modification of growth, mortality, and regeneration processes in forest growth and yield models have been proposed, since increases in temperatures and changes to hydrologic cycles will likely stress these relationships (CROOKSTON *et al.*, 2008). Our ability to make reliable estimates of growth responses to climate change, however, may be limited by our understanding of the interaction between atmospheric CO₂ and the changes in temperatures (EAMUS, 1996).

Operationally, a considerable amount of effort has been expended on developing disease-resistant genotypes of major commercial forest tree species, and this becomes even more critical given the uncertain effects changes in the climate may have on insect and disease issues (YANCHUK and ALLARD, 2009). Since artificial migration of forests has been proposed to facilitate shifts in vegetation patterns, planners should keep in mind that the knowledge gained from previous empirical research may not be transferable to tree species that have been established outside of their current natural range (YANCHUK and ALLARD, 2009). As a result, controlled planting trials, accompanied by monitoring and evaluation processes, should precede widespread planting of tree species outside their current ranges (THORPE *et al.*, 2006). Genetic guidelines for reforestation should also be periodically reviewed (BLATE *et al.*, 2009).

In general, warmer areas of the world may see an increase in the net primary production of forests (RAY, 2008), however the effects will vary regionally. For example, under some modeling scenarios, net primary productivity and could be reduced, and water yield increased (due to lower leaf areas) in the present range of loblolly pine (*Pinus taeda*) in the southern United States (McNULTY *et al.*, 1996). In other areas, such as the northern United States, and under other scenarios, net primary productivity and could be increased and water yield decreased (ABER *et al.*, 1995). In sum, the direction and magnitude of the impact of climate change on net primary production is largely dependent on the degree of warming and the associated impacts on precipitation (CHIANG *et al.*, 2008). In most areas of the world, the effects of climate change on the growth of forests will also arise from changes in the normal growing season length (longer or shorter), and perhaps suggest that a

fertilization effect on forests from additional carbon dioxide should be considered (HUANG *et al.*, 1998). However, while an increase in carbon in the atmosphere may provide a fertilization effect, the development of soil conditions, particularly at higher elevations, may progress at a rate slower than necessary (BOSWORTH *et al.*, 2008). Forest growth may also increase where soil conditions are suitable for the retention of increased precipitation, along with the positive feedback from carbon and nitrogen cycles that amplify the responses (PASTOR and POST, 1988). For example, MONSERUD *et al.* (2008) suggest that the site index for lodgepole pine in Alberta (Canada) will increase by about 1 meter per year, although the range of lodgepole pine may eventually shift due to changes in precipitation levels. Others have noted that while elevated atmospheric carbon levels may enhance near-term forest growth in areas where water and nitrogen are not in short supply, other industrial pollutants (in addition to climate stress) may actually decrease forest growth in the longer term (BLATE *et al.*, 2009). Many currently available empirical forest growth and yield models assume that future growing conditions will be similar to recent past growing conditions and the interaction of these with natural regeneration, ingrowth, mortality, and species-interaction processes. Process-based growth and yield models, however, may provide a framework within which one can estimate forest growth responses to a changing climate (GARCIA-GONZALO *et al.*, 2008).

Currently, there is a scarcity of data on the long-term dynamics of forest tree species under a warming climate (LINDNER *et al.*, 1997). Given the large uncertainties involved, the best one might do at present is to make probabilistic estimates of climate change effects on forest growth (e.g., WOODBURY *et al.*, 1998). These efforts might inform us of the chances that growth and yield of forest products may increase or decline under certain scenarios. One option for forest adaptation that would address the sustainability of forests is for planners and managers to develop alternative silvicultural regimes that are designed to reduce drought stress in trees (BLATE *et al.*, 2009). The selection of tree planting stock and planting methods should also be considered carefully in a long-term forest management plan (BOSWORTH *et al.*, 2008). As a result of these findings, planners should consider the following:

- Adjusting growth rates, mortality, ingrowth, and regeneration assumptions in the growth and yield models that are used to provide the forest management regime data (e.g., potential tree volume over time) necessary for forest planning efforts.
- Considering alternative growth and yield models that account for the interaction of water stress, carbon availability, and subsequent growth responses that are not readily evident in empirical growth and yield models.

Scale of Planning Efforts

The time frame that forest plans cover varies from relatively short (a decade or two) for organizations with a commodity production or economic focus, to relatively long (a century or more) for publicly-managed land management organizations that have broader ecological and social objectives. It is highly unlikely that land management organizations with short planning horizons would address potential changes in the climate through their forest plans. However, if the sustainability of forest resources over the long-run were of interest, longer-term forest plans would seem to be the appropriate venue for accommodating risk and uncertainty related to climatic variables. As one may be aware, local management decisions should be made within the context of the ownership, the landscape, and regional and higher hierarchies, since focusing on a single scale in time or space may obscure processes that are important at larger scales (CROW, 2008). For long-range planning purposes, regional sensitivity of plant species to climate changes and analyses of associated risks need to be evaluated at a scale larger than the administrative boundaries of a landowner (LINDNER *et al.*, 1997). Unfortunately, the data and time available for appropriately recognizing resource conditions outside of an ownership boundary is generally lacking, thus most forest planning efforts today focus on the objectives, goals, and impacts within confined spaces. However, while the spatial resolution of climate change projections is generally inconsistent with typical forest planning management units, the effects can be disaggregated down to the management unit scale (RAY, 2008) if these are desired. As a result, planners who are directed to consider sustainability of forest resources over a long time frame should consider:

- Developing a model that can estimate impacts and disturbance agents beyond the scope of their ownership boundary.
- Developing methods for disaggregating broad-scale estimates of changes to precipitation and temperature patterns down to the local scale inherent in the planning effort.

Carbon Sequestration

One recent challenge for some forest planners has been to balance commodity production (or economic) goals with specific carbon sequestration goals (KRCMAR *et al.*, 2001; GARCIA-GONZALO *et al.*, 2008). Carbon can be considered sequestered in the above-ground stem of trees, in the below-ground root systems, and in the soil of forests. In terms of land management options, some have suggested that short-rotation woody biomass plantations would be of value in sequestering atmospheric carbon, while also providing an alternative energy source (BOSWORTH *et al.*, 2008). Unfortunately, short-rotation forestry is not appropriate in many areas of the world, given the objectives of various land ownerships. Further, when managing older forests and forests represented by uneven-aged manage-

ment regimes, tree mortality releases back into the atmosphere some of the carbon that had been sequestered. Carbon sequestration is also interrelated with wildfire risk, since increases in wildfire frequency may result in changes to forest composition and tree density levels, both of which will ultimately affect carbon pools (WESTERLING *et al.*, 2006). As a result of uncertainties in timber yields (due to a changing temperature and precipitation regimes and CO₂ fertilization effects), and imprecise information on carbon sinks as they relate to the life cycle of carbon in wood and wood products, there is some uncertainty involved in estimating and projecting carbon flows associated with forest management (KRCMAR *et al.*, 2001). Alternative scenarios are currently used by many land managers during the planning process to help understand these management uncertainties, and KRCMAR *et al.* (2001) suggest that these techniques may be of value in understanding the potential effects of climate change on carbon sequestration options. In rather complex forest planning processes, carbon could be modeled as a flux, by accounting for changes in the level stored above-ground as biomass and biomass growth, changes in harvest levels, changes in below-ground storage, and the associated dynamics of carbon stored in products and ultimately released through decay and other processes (KRCMAR *et al.*, 2001). In sum, planners could do the following to recognize the impacts of climate change on carbon sequestered in forests:

- Incorporate methods for estimating the level of carbon sequestered in various forest types and how these stocks will change over time with management activities and potential changes to the climate.
- Develop methods to account for uncertainty in carbon stocks, and analyze the sensitivity of forest management objectives to various levels of uncertainty.

Invasive Species Management

The opportunities for establishment and distribution of invasive plant species are expected to increase with changes in the climate, and the area potentially affected will pose a problem for land management planners (BARDSLEY and EDWARDS-JONES, 2007; BOSWORTH *et al.*, 2008). Increases in atmospheric carbon may be partly responsible for the spread of invasive plants (BOSWORTH *et al.*, 2008), and the spread of exotic species and diseases may involve multiple scales of interacting environmental factors (CROWL *et al.*, 2008). Additional information may be required to adequately assess the drivers of invasive species range changes over space and time, and in relation to climate change and human management of the landscape (CROWL *et al.*, 2008). As a result, taking defensive actions through management at key migration points may help block or remove invasions and increase resistance (MILLAR *et al.*, 2007). Some have suggested that management plans that incorporate intensive management options may be appropriate

in areas where establishment may enable the retention of desired species (MILLAR *et al.*, 2007). As a result, the following actions could be taken by forest planners to more closely account for invasive species in forest plans:

- Incorporate functional relationships that describe the establishment, growth, and effects of invasive species on forests into forest planning efforts.
- Develop forest management regimes that could act to mitigate the spread of invasive species and the subsequent effects of invasive species on forest growth and forest health.

Acknowledgement of Uncertainty

Many of the previous topics have suggested that uncertainty and risk need to be acknowledged in order to increase the resilience of forests to potential changes in the climate, and to facilitate shifts in vegetation patterns and recognize changes in land use. Unfortunately, and perhaps inherent in the nature of humans, management under uncertainty is often viewed as annoying and confusing, and in many cases of forest planning, uncertainties are ignored in economic and ecological relationships (PAOLI and BASS, 1997). The treatment of uncertainty can be challenging and time-consuming, yet a thorough examination of the uncertainties may change what is regarded as the best course of action for management (PAOLI and BASS, 1997). Some suggest that planning for uncertainty is the best option for forest management, so that risks can be minimized by considering and implementing multiple courses of action (MILLAR *et al.*, 2007). While simulation models and heuristics may be well-suited for modeling uncertainties in forest management planning, linear programming and mixed-integer programming are more widely used today to develop forest plans (BETTINGER *et al.*, 2009). Unfortunately, it is difficult to account for uncertainty in these latter two types of planning models, since it is generally assumed that all technical coefficients would be known with certainty before a planning problem is solved. However, PAPPS (2000) provides an example of incorporating stochastic forest management relationships into linear programming, and a number of others have incorporated stochastic relationships into forest planning processes that recognize natural disturbances (e.g., GASSMANN, 1989; ARMSTRONG, 2004; YANG *et al.*, 2004). As a result, planners should:

- Investigate methods for incorporating stochastic relationships into forest planning models, particularly when the functional relationships within models (whether they are growth and yield models, water yield models, or natural disturbance models) are necessary to more adequately represent the current state of knowledge in these areas.

CONCLUSIONS

Although forest plans are always developed under conditions that contain risk and uncertainty, no matter the length of the planning horizon (BRICENO-ELIZONDO *et al.*, 2008), these uncertainties and risks may be ignored, thus bold new forest management strategies have been called for in the management of forests in response to potential changes in the climate (YANCHUK and ALLARD, 2009). HALPIN (1997) further suggested that forest managers must be creative and explore new techniques in management planning to assess the impacts of potential changes in the climate, and went further to suggest that a regional-level view would be more appropriate than a land-owner-centric planning process which is typical of most operational planning efforts. Thus the consensus among the recent research is that long-range planning efforts need to incorporate risk and uncertainty into planning efforts to understand where the vulnerabilities exist, where areas of resilience lie, and how tree species shifts will impact overall management objectives (NITSCHKE and INNES, 2008). Unfortunately, risks are difficult to predict given the ecological, economic, and social framework within which they must be couched and the climatic thresholds that may occur and result in irreversible impacts on an ecosystem (NITSCHKE and INNES, 2008). Further, the task of deciding how to judge the significance of these actions, and how to interpret the ecological responses and vulnerabilities, is not perfectly clear, since these decisions and interpretations are made by decision-makers and land managers who must consider other issues outside of the planning system (NITSCHKE and INNES, 2008). In a typical forest planning process alternative forest plans are developed, their consequences are ranked, and values are placed on them in a relatively subjective manner by the decision-makers and land managers (BRICENO-ELIZONDO *et al.*, 2008).

The broader implication associated with the suggestions made here is that planners need to develop multiple scenarios that assign risk at different levels, and that these scenarios may be necessary for land managers and decision-makers to more fully understand the sensitivity of forest plan results to the uncertainties that lie ahead (GARCIA-GONZALO *et al.*, 2008). This concern is particularly relevant in planning efforts that seek to incorporate stochastic relationships related to natural disturbances and commodity production goals, thus some have suggested that stochastic planning models (LOHMANDER, 2007) or models that include fuzzy set relationships (BRICENO-ELIZONDO *et al.*, 2008) are more appropriate in these instances than more commonly-used deterministic models such as linear programming. In sum, ignoring the potential changes to the landscape that may occur over long periods of time may result in inaccurate estimates of timber production and ecological services (BRICENO-ELIZONDO *et al.*, 2008).

Much of the recent research also suggests that management actions must be designed to promote resilience and therefore reduce the risk of natural disturbances; these ap-

proaches have been called at times "climate-smart" (NITSCHKE and INNES, 2008). When considering climate change, forest management plans should address changes in precipitation patterns, fire regimes, tree physiology, and landscape patterns and processes (BLATE *et al.*, 2009). Obviously, value judgments on behalf of land managers and policy-makers will likely be used to assess the advantages and disadvantages of man's attempt to manipulate the environment in response to climate change (THORPE *et al.*, 2006). This is because the information we possess about the effect of climate change on forest resources is not as robust as the information we possess about vegetation dynamics in our current system. However, even if planners were able to account for all of the potential changes in forest ecosystem dynamics at an ownership (or larger) scale, the resulting management problem, when quantified, may become computationally intractable (KRCMAR *et al.*, 2001).

Land use change is a compounding factor in forest planning, since as one plans for shifts in forest composition, changes in land uses need to be estimated along with (perhaps) further fragmentation of the forested landscape. Ecological restoration of forests has been repeatedly called for in response to the increases in wildfire risk, yet actions along these lines may not be sufficient to reverse current trends in wildfire behavior. Decision-support systems such as the one suggested by GÄRTNER *et al.* (2008) can be used to help land managers and decision-makers think through the various options for managing a landscape in light of changes to the climate. And shorter-term land management planning processes that provide flexibility in management activities in order to reduce risks over a single tree rotation period have also been suggested even if these actions do not lead to improvements in forest yields (NITSCHKE and INNES, 2008). In general, a reduction in the stressors that increase the vulnerability of forests (fragmentation, pollution, invasive species, altered fire regimes) has been proposed as a goal for forests to allow them to withstand the impacts of climate change (GLICK *et al.*, 2009). Also proposed as hedges against changes in the climate are the need to build redundancy in forest types, the need to provide reserves of various types of habitat, and the need to maintain connectivity of habitat (HALPIN, 1997). While intensive forest management, as we noted earlier, can help solve some of the problems associated with potential changes to the climate, some have also suggested that uneven-aged forest management may be more appropriate for areas that have both low resilience and low disturbance risk (NITSCHKE and INNES, 2008).

As with any forest planning analysis, the results of alternatives need to be communicated to the decision-makers in a manner that facilitates informed and semi-rational decisions. This is even more important in cases where abstract and uncertain aspects of climate change are factored into management scenarios (DOCKERTY *et al.*, 2006). In addition to the maps and tabular summaries that describe alternative management scenarios, DOCKERTY *et al.* (2006) suggest that digital photo

montages that depict somewhat realistically how a landscape will change over time may be of value in helping decision makers consider alternative policies. Perhaps more importantly, there is a need to increase the technical understanding of the issues involved, through the development of educational materials aimed at employees, managers, and other stakeholders (BLATE *et al.*, 2009). Unfortunately for forest planning processes, these suggestions, along with those proposed earlier in this review, will require additional time, cost, and effort on behalf of planners. It remains unclear whether forest management organizations will devote the resources necessary to more fully account for effects beyond ownership boundaries, changes in growth rates, effects on carbon sequestration, natural disturbances (and changes in their timing, intensity, size and duration), and other uncertainties. Public pressure to recognize these concerns may force some organizations to make adjustments to their planning processes, yet the more financially-savvy management organizations will likely balance the cost associated with additional investments in planning processes with estimates of future benefits of having done so. In this latter case, some organizations may decide to forgo many of the suggested changes in quantitative planning processes and consider strategic alternatives in a more qualitative manner.

LITERATURE CITED

- ABER, J.D., OLLINGER, S.V., FEDERER, C.A., REICH, P.B., GOULDEN, M.L., KICKLIGHTER, D.W., MELILLO, J.M. and LATHROP, R.G. Jr., (1995): Predicting the effects of climate change on water yield and forest production in the northeastern United States. *Climate Research* 5: 207-222
- ARMSTRONG, G.W., (2004): Sustainability of timber supply considering the risk of wildfire. *For. Sci.* 50: 626-639
- BARDSLEY, D.K. and EDWARDS-JONES, G., (2007): Invasive species policy and climate change: Social perceptions of environmental change in the Mediterranean. *Environ. Sci. Policy* 10: 230-242
- BETTINGER, P., BOSTON, K., SIRY, J.P. and GREBNER, D.L., (2009): *Forest management and planning*. Academic Press, New York, 331pp
- BETTINGER, P., HOLLIDAY, C.P., THREADGILL, M.S. and HYLDAHL, C.A., (2007): On integrating water yield models with forest planning efforts. *Water Policy* 9: 631-643
- BINKLEY, C.S. and VAN KOOTEN, G.C., (1994): Integrating climate change and forests: Economic and ecologic assessments. *Climatic Change* 28: 91-110
- BLATE, G.M., JOYCE, L.A., LITTELL, J.S., McNULTY, S.G., MILLAR, C.I., MOSER, S.C., NEILSON, R.P., O'HALLORAN, K. and PETERSON, D.L., (2009): Adapting to climate change in United States national forests. *Unasylva* 60(1/2): 57-62
- BOSWORTH, D., BIRDSEY, R., JOYCE, L. and MILLAR, C., (2008): Climate change and the nation's forests: Challenges and opportunities. *J. For.* 106(4): 214-221
- BRICENO-ELIZONDO, E., JÄGER, D., LEXER, M.J., GARCIA-GONZALO,

- J., PELTOLA, H. and KELLOMÄKI, S., (2008): Multi-criteria evaluation of multi-purpose stand treatment programmes for Finnish boreal forests under changing climate. *Ecological Indicators* **8**: 26-45
- CAMPBELL, K.A. and DEWHURST, S.M., (2007): A hierarchical simulation-through-optimization approach to forest disturbance modelling. *Ecol. Model.* **202**: 281-296
- CARMEL, Y. and FLATHER, C.H., (2006): Constrained range expansion and climate change assessments. *Frontiers in Ecology and the Environment* **4**: 178-179
- CHIANG, J.M., IVERSON, L.R., PRASAD, A. and BROWN, K.J., (2008): Effects of climate change and shifts in forest composition on forest net primary productivity. *J. Integ. Plant Biol.* **50**: 1426-1439
- CLARK, J.S., (1998): Why trees migrate so fast: Confronting theory with dispersal biology and the paleorecord. *The American Naturalist* **152**: 204-224
- CROOKSTON, N.L., REHFELDT, G.E., FERGUSON, D.E. and WARWELL, M., (2008): FVS and global warming: A prospectus for future development. In: HAVIS, R.N. and CROOKSTON, N.L. (eds) Third forest vegetation simulator conference, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. Proceedings RMRS-P-54: 7-16
- CROW, T.R., (2008): Managing forest landscapes for climate change. In: LAFORTEZZA, R. *et al.* (eds) Patterns and processes in forest landscapes. Springer, Dordrecht, The Netherlands: 33-43
- CROWL, T.A., CRIST, T.O., PARMENTER, R.R., BELOVSKY, G. and LUGO, A.E., (2008): The spread of invasive species and infectious disease as drivers of ecosystem change. *Frontiers in Ecology and the Environment* **6**: 238-246
- DAVIS, A.J., JENKINSON, L.S., LAWTON, J.H., SHORROCKS, B. and WOOD, S., (1998): Making mistakes when predicting shifts in species range in response to global warming. *Nature* **391**: 783-786
- DOCKERTY, T., LOVETT, A., APPLETON, K., BONE, A. and SÜNNENBERG, G., (2006): Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes. *Agriculture, Ecosystems and Environment* **114**: 103-120
- DYER, J.M., (1994): Land use pattern, forest migration, and global warming. *Landscape and Urban Planning* **29**: 77-83
- EAMUS, D., (1996): Tree responses to CO₂ enrichment: CO₂ and temperature interactions, biomass allocation and stand-scale modeling. *Tree Physiology* **16**: 43-47
- GARCIA-GONZALO, J., LEXER, M.J., PELTOLA, H. and KELLOMÄKI, S., (2008): Designing a forested landscape in Finland under different climate scenarios. In: von Gadow, K., and Pukkala, T. (eds) Designing green landscapes. Springer, New York: 215-241
- GÄRTNER, S., REYNOLDS, K.M., HESSBURG, P.F., HUMMEL, S. and TWERY, M., (2008): Decision support for evaluating landscape departure and prioritizing forest management activities in a changing environment. *For. Ecol. Manage.* **256**: 1666-1676
- GASSMANN, H.I., (1989): Optimal harvest of a forest in the presence of uncertainty. *Can. J. For. Res.* **19**: 1267-1274
- GILLET, N.P., WEAVER, A.J., ZWIERS, F.W. and FLANNIGAN, M.D., (2004): Detecting the effect of human induced climate change on Canadian forest fires. *Geophysical Research Letters* **31**: L18211
- GLICK, P., STAUDT, A. and STEIN, B., (2009): A new era for conservation: Review of climate change adaptation literature. National Wildlife Federation, Reston, VA, 69pp
- HALPIN, P.N., (1997): Global climate change and natural-area protection: Management responses and research directions. *Ecol. Appl.* **7**: 828-843
- HARTLEY, I. and MARSHALL, P., (1997): Modelling forest dynamics in the Mackenzie Basin under a changing climate. In: COHEN, S.J. (ed) Mackenzie Basin Impact Study (MBIS) final report. Environment Canada and University of British Columbia, Vancouver, British Columbia: 146-156
- HODGES, D.G., CUBBAGE, F.W. and REGENS, J.L., (1992): Regional forest migrations and potential economic effects. *Environmental Toxicology and Chemistry* **11**: 1129-1136
- HUANG, G.H., COHEN, S.J., YIN, Y.Y. and BASS, B., (1998): Land resources adaptation planning under changing climate - a study for the Mackenzie Basin. *Resources, Conservation and Recycling* **24**: 95-119
- INNES, J., JOYCE, L.A., KELLOMÄKI, S., LOUMAN, B., OGDEN, A., PARROTTA, J., THOMPSON, I., AYERS, M., ONG, C., SANTOSO, H., SOHNGEN, B. and WREFORD, A., (2009): Management for adaptation. In: SEPPÄLÄ, R., BUCK, A. and KATILA, P. (eds) Adaptation of forests and people to climate change - a global assessment report. International Union of Forest Research Organizations, Vienna, Austria. IUFRO World Series Vol. **22**: 135-169
- KADONAGA, L., (1997): Forecasting future fire susceptibility in the Mackenzie Basin. In: COHEN, S.J. (ed) Mackenzie Basin Impact Study (MBIS) final report. Environment Canada and University of British Columbia, Vancouver, British Columbia: 157-165
- KRCMAR, E., STENNES, B., VAN KOOTEN, G.C. and VERTINSKY, I., (2001): Carbon sequestration and land management under uncertainty. *Eur. J. Oper. Res.* **135**: 616-629
- LINDNER, M., BUGMANN, H., LASCH, P., FLECHSIG, M. and CRAMER, W., (1997): Regional impacts of climatic change on forests in the state of Brandenburg, Germany. *Agric. For. Meteorol.* **84**: 123-135
- LOHMANDER, P., (2007): Adaptive optimization of forest management in a stochastic world. In: WEINTRAUB, A., ROMERO, C., BJØRNDAL, T. and EPSTEIN, R. (eds) Handbook of operations research in natural resources. Springer, New York: 525-543
- MARTIN, P.H., (1996): Climate change, water stress, and fast forest response: a sensitivity study. *Climatic Change* **34**: 223-230
- M McNULTY, S.G., VOSE, J.M. and SWANK, W., (1996): Potential climate change effects on loblolly pine forest productivity and drainage across the southern United States. *Ambio* **25**: 449-453

- MILLAR, C.I., STEPHENSON, N.L. and STEPHENS, S.L., (2007): Climate change and forests of the future: Managing in the face of uncertainty. *Ecol. Appl.* **17**: 2145-2151
- MITCHELL, N., ESPIE, P. and HANKIN, R., (2004): Rational landscape decision-making: The use of meso-scale climatic analysis to promote sustainable land management. *Landscape and Urban Planning* **67**: 131-140
- MONSERUD, R.A., YANG, Y., HUANG, S. and TCHEBAKOVA, N., (2008): Potential change in lodgepole pine site index and distribution under climate change in Alberta. *Can. J. For. Res.* **38**: 343-352
- NITSCHKE, C.R. and INNES, J.L., (2008): Integrating climate change into forest management in South-Central British Columbia: An assessment of landscape vulnerability and development of a climate-smart framework. *For. Ecol. Manage.* **256**: 313-327
- PAOLI, G. and BASS, B., (1997): Editorial: Climate change and variability, uncertainty and decision-making. *J. Environ. Manage.* **49**: 1-6
- PAPPS, S., (2000): Harvest planning with uncertain prices and demands. In: VASIEVICH, J.M., FRIED, J.S. and LEEFERS, L.A. (eds) Seventh symposium on systems analysis in forest resources. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN. General Technical Report NC-205: 241-248
- PASTOR, J. and POST, W.M., (1988): Response of northern forests to CO₂-induced climate change. *Nature* **334**: 55-58
- PEARSON, R.G. and DAWSON, T.P., (2005): Long-distance plant dispersal and habitat fragmentation: Identifying conservation targets for spatial landscape planning under climate change. *Biol. Conserv.* **123**: 389-401
- RAVINDRANATH, N.H., JOSHI, N.V., SUKUMAR, R. and SAXENA, A., (2006): Impact of climate change on forests in India. *Current Science* **90**: 354-361
- RAY, D., (2008): Impacts of climate change on forestry in Scotland - a synopsis of spatial modelling research. Forestry Commission Scotland, Edinburgh. Research Note 101. 8pp
- SCHWARTZ, M.W., IVERSON, L.R., PRASAD, A.M., MATTHEWS, S.N. and O'CONNOR, R.J., (2006): Predicting extinctions as a result of climate change. *Ecology* **87**: 1611-1615
- SIEBEN, B., SPITTLEHOUSE, D.L., MCLEAN, J.A. and BENTON, R.A., (1997): White pine weevil hazard under GISS climate change scenarios in the Mackenzie Basin using radiosonde derived lapse rates. In: COHEN, S.J. (ed) Mackenzie Basin Impact Study (MBIS) final report. Environment Canada and University of British Columbia, Vancouver, British Columbia: 166-175
- SUN, G., McNULTY, S.G., MOORE-MYERS, J.A. and COHEN, E.C., (2008): Impacts of multiple stresses on water demand and supply across the southeastern United States. *J. Am. Water Res. Ass.* **44**: 1441-1457
- THORPE, J., HENDERSON, N. and VANDALL, J., (2006): Ecological and policy implications of introducing exotic trees for adaptation to climate change in the western boreal forest. Saskatchewan Research Council, Saskatoon, Saskatchewan. SRC Publication No. 11776-1E06
- TURNER, M.G. and ROMME, W.H., (1994): Landscape dynamics in crown fire ecosystems. *Landscape Ecol.* **9**: 59-77
- WANG, S., ZHANG, Z., SUN, G., McNULTY, S.G., ZHANG, H., LI, J. and ZHANG, M., (2008): Long-term streamflow response to climatic variability in the Loess Plateau, China. *J. Am. Water Res. Ass.* **44**: 1098-1107
- WESTERLING, A.L., HIDALGO, H.G., CAYAN, D.R. and SWETNAM, T.W., (2006): Warming and earlier spring increase western U.S. forest wildfire activity. *Science* **313**: 940-943
- WILSON, L.S., (1981): The World's changing climate - some issues for planners. *Long Range Planning* **14**(5): 83-89
- WOODBURY, P.B., SMITH, J.E., WEINSTEIN, D.A. and LAURENCE, J.A., (1998): Assessing potential climate change effects on loblolly pine growth: A probabilistic regional modeling approach. *For. Ecol. Manage.* **107**: 99-116
- YANCHUK, A. and ALLARD, G., (2009): Tree improvement programmes for forest health - can they keep pace with climate changes? *Unasylva* **60** (1/2): 50-56
- YANG, J., HE, H.S. and GUSTAFSON, E.J., (2004): A hierarchical fire frequency model to simulate temporal patterns of fire regimes in LANDIS. *Ecol. Model.* **180**: 119-133

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