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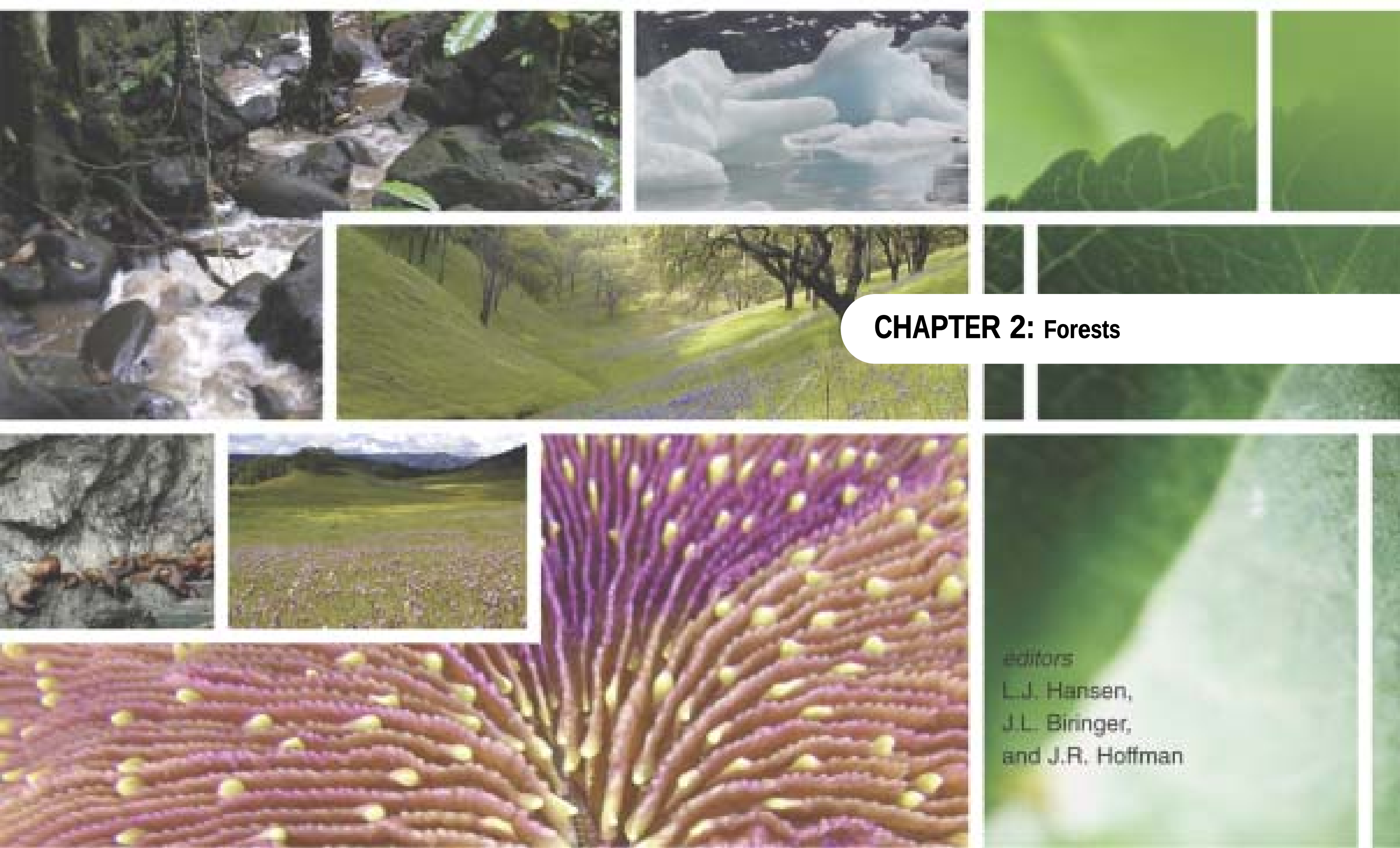
BUYING TIME:

A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems



CHAPTER 2: Forests

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Forest Ecosystems Threatened by Climate Change: Promoting Long-term Forest Resilience

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CURRENT RATES OF CLIMATIC WARMING are the highest they have been in the last 10,000 years (IPCC, 1996a). Against this backdrop are forests and forest ecosystems, which have persisted for hundreds of millions of years. During this time major fluctuations in the climate have caused vegetation to modify their composition, structure and function, or risk extinction. Forests as a biome have tolerated such climatic changes through their ability to migrate, relatively unencumbered, to suitable new habitat. Past changes have also occurred at a much slower pace than those seen today, allowing forests time to adapt. Many of today's forests, however, have undergone serious fragmentation and degradation from roads, agriculture and development, and are thus impeded in their ability to migrate as their local climate changes (Noss, 2000). It is in combination with these threats that the impacts of unprecedented rates of climate change can compromise forest resilience, and distribution (IPCC, 2001).

The following sections lay out the chief stresses to each of the different forest types from tropical regions to boreal forests, as well as the crucial components of each system that must be maintained for healthy ecosystem functioning. Then evidence of current impacts on each major forest type is reviewed, together with projections of likely future impacts determined from General Circulation Models (GCMs) and other scientific research. Analysis of these existing and future non-climate threats applied together with an overlay of climate change impacts for a particular forest type or ecoregion will help conservationists understand what protection and other management options are available to enhance forest resilience in the face of climate change.

Stresses and Vulnerabilities Due to Factors Other Than Climate Change

Forests cover almost a third of the Earth's landmass, representing the most substantial reservoir of terrestrial biological diversity. Scientists estimate that forests contain as much as two-thirds of all known terrestrial species (FAO, 2000). However, many forest-dwelling large mammals, half the large primates, and nearly 9% of all known tree species are at some risk of extinction (WRI, 2000).

About half of the world's original and intact "frontier" forest has been lost since the dawn of agriculture some 8,000 years ago (FAO, 2000). Just one fifth of original forests exist in large and relatively natural ecosystems (Dirk et al., 1997). Most forest loss has occurred in the last three decades, largely due to human impacts. Deforestation has been most absolute in the Temperate Zone, where only a fraction of the original intact forest still remains in scattered fragments (FAO, 2000). Close to 15 million hectares of largely tropical natural forests are lost each year, equal to an area the size of Nepal (FAO, 2000). In addition, 1.5 million hectares are converted to forest plantations every year. The major cause of forest loss is conversion to other land uses as well as fragmentation from logging, agriculture, and settlement. Scientists assert that this has already resulted in the beginning of the 6th great extinction, and the first to be perpetuated by humans (Chapin et al., 2000).

Although forest cover is stable in the boreal region, and slightly increasing in the temperate zone after prior deforestation, these trends hide the fact that the *quality* of these forests has deteriorated drastically, impoverishing wildlife habitat for species dependent upon intact forest and unraveling ecosystem functions (FAO, 2000).

An overview of existing and future non-climate threats to each of the major forest types is below, followed by a summary of possible or likely impacts from climate change itself. A broad-brush analysis of these threats in combination with a discussion of the crucial components for each forest type provides a baseline for evaluating how resilient each type will be in the future once an overlay of probable climate change impacts are applied. Examples of threats to particular forest ecoregions are given in some instances to illustrate a more detailed level of analysis of vulnerability to climate change.

TROPICAL AND SUBTROPICAL MOIST BROADLEAF FORESTS

Tropical and Subtropical Moist Forests are extremely sensitive to disturbances such as plowing, overgrazing, and excessive burning due to limiting climatic and soil conditions. The dominant current threats to this forest type aside from climate change include conversion to agricultural land as well as large-scale commercial logging. An area the size of Ireland is lost due to conversion every few years within the tropical and subtropical region (FAO, 2000). This forest loss, combined with the introduction of exotics on islands, is the primary driver behind a high rate of species extinction (WWF, 2003a).

Looking at the immediate pressures to the health and functioning of a specific ecoregion is necessary before applying an overlay of climate change scenarios in order to help identify management options. The Eastern Arc Montane Forests of Kenya and Tanzania are among the oldest mountain ranges in Africa, and provide an illustrative example. As is true with most mountainous regions in Africa, this forest system is isolated from other similar areas by great expanses of lowland habitats. Isolation has produced a high level of endemism with many local species of plants and animals restricted to single mountain ranges. These microhabitats have experienced relatively moist conditions for long periods of time, even during drying trends throughout much of the rest of Africa. Very little of the Eastern Arc Montane Forests is under protected status, though all of the mountains are under pressure from agricultural expansion on lower slopes, firewood collection, and grazing (WWF, 2003b). Careful analysis of these existing and future non-climate threats applied together with an analysis of climate change impacts will help conservationists understand what protection and other management options are available to augment migration possibilities for endemic species that may be challenged with excessive changes in temperature and precipitation regimes within this ecoregion.

TROPICAL AND SUBTROPICAL DRY BROADLEAF FORESTS

Tropical and subtropical dry forests require large natural areas in order to maintain large predators and other vertebrates, to buffer sensitive species from hunting pressure, and to absorb occasional large fire events. Many dry forest species are reliant upon water sources and the persistence of riparian forests. In general, dry forests are extremely sensitive to excessive burning and deforestation, overgrazing and the introduction of exotic species. Restoration is possible though can be particularly challenging in intensely degraded areas. (WWF, 2003c)

In the Mexican Dry Forest, a growing urban population, increasing tourism and exploitation of wildlife are extremely serious threats to the ecoregion. Changing land uses for road construction, perennial plantations, and ranch farms are also a source of concern. (WWF, 2003d) A detailed layout of these threats, together with information on the distribution of sensitive species would serve as a preliminary step to analyzing this ecoregion's vulnerability to climate change.

TROPICAL AND SUBTROPICAL CONIFEROUS FORESTS

Healthy tropical and subtropical coniferous forests are of sufficient size to withstand disturbances such as fire, windthrow, and outbreaks of disease. Several species, as well as successional processes are dependent on fire, however. Late-successional species, which are highly sensitive to logging and fragmentation due to slow regeneration rates, require special attention in management plans. Exotics also can have extensive impacts on these forests.

The Mesoamerican Pine-Oak Forests of El Salvador, Guatemala, Honduras, Mexico, and Nicaragua contain among the world's most extensive subtropical coniferous forests, with many plant and animal species limited to particular locales. This ecoregion is also under pressure from fragmentation due to commerical logging, overgrazing by livestock, and conversion to agriculture.

TEMPERATE BROADLEAF AND MIXED FORESTS

Temperate broadleaf and mixed forests have been degraded and deforested to a great extent through habitat conversion, resource extraction, and through the introduction of exotic species (Wilcove et al., 1998). Carnivores inhabiting these forests have large home ranges, and forests must be of adequate size to maintain resilience to large-scale disturbance events such as fire. Late-successional forests are vital for the survival of many plants, lichen, fungi and invertebrates in this ecosystem. (WWF, 2003e) Some species inhabiting these forests show great sensitivity to fragmentation. This list includes breeding songbirds exposed to parasitism or elevated nest predation, as well as many forest understory species whose migration to other suitable forest is hindered by deforested areas. The loss of large native predators has substantial cascading effects on forest structure and ecology; and the introduction of exotic species can have large impacts on native communities as well. However, restoration potential for this forest type is high.

The Southwest China Temperate Forests, home to the giant panda *(Ailuropoda melanoleuca)* and many other rare species, contain some of the richest assemblages of temperate forest trees in the world and exhibit high endemism and unusal biogeographic patterns. Conversion to agriculture and fragmentation and degradation for timber are the principal threats to this ecoregion. (WWF, 2003f) A map of the distribution of where fragmentation and degradation is occuring, together with an analysis of crucial habitat will provide the baseline necessary to analyze climate change threats so that conservation plans can be adjusted accordingly.

TEMPERATE CONIFEROUS FORESTS

Temperate coniferous forests likewise require sufficient patch sizes in order to maintain larger carnivores which are extremely wide-ranging, as well as species that track resources that may vary widely in time and space with disease outbreaks, fires, and cone production. Large carnivores are highly sensitive to encroachment upon their home ranges, and many species are sensitive to habitat fragmentation, particularly of late-successional species which may regenerate slowly. Fires are necessary in many temperate forests in order to maintain successional processes. (WWF, 2003g)

The Altai-Sayan Montane Forests are experiencing a number of threats, including clearance of the forest, over-collection of plants and hunting along the banks of larger rivers and in heavily populated areas such as the Kusnetsk Basin, Salair, Alatau Kuznetsk and southwestern Altai. Overgrazing and associated erosion is a problem in some alpine and sub-alpine areas, as is mining and the threat of extensive wildfires that have engulfed large areas within the ecoregion. (WWF, 2003h)

BOREAL FORESTS

Boreal forests suffer from a variety of atmospheric threats unrelated to climate change, such as acid rain, UV-B radiation (from depletion of atmospheric ozone), and smog. There are also direct threats, including degradation from logging, mining and oil extraction, pipelines, and roads. Extreme weather events, such as ice storms, are highly damaging to trees (and could become increasingly prevalent as climate patterns shift).

At the same time, it is important to take into account those aspects of boreal forests that are crucial to its long-term viability. Natural disturbances such as fires, which cycle nutrients, and pests and diseases, which allow the introduction of early successional species by killing off adult trees, are often carefully balanced. (Sekula, 2000). In the Canadian Boreal Forests, man-made activities threaten the extent of the forest. Mining activities in the north, and logging in the southwest are constraints to healthy ecosystem function.

MEDITERRANEAN FORESTS

Mediterranean forests have largely been degraded through conversion to agriculture, pasture and to urban development. Fire, logging, the introduction of exotics, and intensive grazing are all present threats as well. Native mediterranean forests are very sensitive to habitat fragmentation, grazing, and alteration of fire regimes (through overburning or fire suppression). The loss of natural groundwater in many Mediterranean regions also has large-scale impacts on biodiversity through the alteration of riverine and floodplain systems. Protection of riparian areas, and blocks of native habitat large enough to sustain regular fire events by leaving sufficient unburned areas to retain genetic diversity are crucial (WWF, 2003i).

MANGROVES

Mangroves play an integral role in the coastal ecosystem, and are of invaluable local and global ecological, economic and social importance. Mangroves live in estuarine settings, acting as a buffer between marine and freshwater systems. In this capacity they are known to act as a filter of local water and can protect shorelines from eroding forces. Mangrove forests also protect seagrass beds and coral reefs from deposition of suspended matter that is transported seaward by rivers. This forest type inhabits waterlogged, salty soils along coasts in the tropics and subtropics where they experience tidal flow. Mangroves are dependent upon a relatively stable hydrographic and salinity regime, and they are susceptible to pollution and the alteration of salinity levels.

Mangroves currently suffer from large-scale conversion and degradation (Ellison and Farnsworth, 1997). In some countries such as India, the Philippines and Vietnam, over 50% of mangrove ecosystems have been lost in the last hundred years. Mangrove trees are harvested for timber, fuel, or pulp, and are also cleared for aquaculture or other development. Deterioration of a mangal occurs when the mangrove is clearcut, when the water flow pattern is disrupted, or when the water level becomes too high so that the aerial roots are unable to obtain oxygen. Pollution, particularly oil, can also interfere with the exchange of gas from mangal roots.

The Gulf of Guinea contains Africa's most extensive mangroves, which help to stabilize a large part of the West African shoreline. Forming a dense barrier between sea and land, the mangrove is a crucial food reservoir for coastal people who rely on its supply of shrimp and crabs, as well as its wood for fuel. It is also a vital host to a number of endangered species, including the African manatee, pygmy hippopotamus, and clawless otter. The area is currently under high stress from urbanization, industrialization, and agriculture, and is experiencing impacts from timber and petroleum exploitation around the Gulf coast.

Assess Present and Future Stress and Vulnerability Due to Climate Change

A warmer climate and changes in precipitation patterns will cause disparate effects on forest ecosystems, making some contract while others will expand. Increases in CO_2 will compound this effect in some systems while dampening the impacts in other systems. Together this indicates that many areas, especially those habitats along environmental gradients, will be subjected to change, and if the population cannot adapt or move with changes in climate, they will face extinction.

Globally, it has been estimated that at least one-third of the world's remaining forests may be adversely impacted by climate change over the next century (IPCC, 1995). Climate change may force species to migrate or shift their ranges far faster than they are able to, thereby disrupting existing ecosystems (Kirilenko et al., 2000; Stewart et al., 1997). Forests may experience changes in fire intensity and frequency, increased susceptibility to insect damage or diseases, and extreme weather events which they may not be adapted to survive (IPCC, 2001).

Predictions for the impacts climate change will continue to have on forests are gathered in a number of ways. At a large scale, it is possible to predict major shifts in biome types by combining biogeography models such as the Holdridge Life Zone Classification Model with general circulation models (GCMs) that project changes under a doubled CO_2 scenario. Biogeochemistry models simulate the gain, loss and internal cycling of carbon, nutrients, and water-impact of changes in temperature, precipitation, soil moisture, and other climatic factors that give clues to ecosystem productivity. Dynamic global vegetation models integrate biogeochemical processes with dynamic changes in vegetation composition and distribution. Studies on particular species comparing present trends with paleological data also provide indications for how species will weather or adapt to future climate change. (Hansen et al., 2001)

Forests are both directly and indirectly impacted by climate change. The direct impacts of warming temperatures and changes in precipitation patterns or extreme weather events on forests are already evident in certain tree and animal species (IPCC, 2001). Even small changes in temperature and precipitation can have significant affects on forest growth and survival (e.g., for certain species of pine; Rehfeldt, 1999; and in tropical montane cloud forests; Hilbert et al., 2001; Pounds et al., 1999), particularly those in threshold areas or at the margins of an ecosystem. Higher temperatures increase water loss through evapotranspiration, which result in drier conditions, as well as decreasing a plant's efficiency of water use (NRC, 2002). Increases in temperature can also have dramatic implications for the timing of flowering and fruiting for plants (Beaubien and Freeland, 2000; Bazazz, 1998), and can also directly affect growth rates and other physiological factors that will cause species to migrate or become extinct. Forests will also be directly threatened by changes in the seasonality of precipitation and increases in extreme weather events such as hurricanes, flooding, lightning, and wind storms (Dale et al., 2001; Hansen et al., 2001; IPCC, 2001; NAST, 2001; Peterson, 2000). Forest characteristics and age-class structure play a large role in determining how a forest will respond to changes in moisture conditions (NRC, 2002). Mature forests have well-established root systems, and are therefore better able to withstand drought-like conditions, whereas younger forests and post-disturbance stands are more vulnerable to decreases in moisture (Gitay et al., 2001). Some species are also more tolerant to variable moisture conditions than others.

Disturbances are a natural part of the functioning of forest ecosystems, and are integral in bringing about succession. Most forests are in some state of reestablishment after disturbances, which themselves result in a change in ecosystem function as species composition and the structure of the forest changes. However, an extreme change in forest structure and function can take place when disturbances exceed their natural range of variation (Dale et al., 2000). Climate change affects forests both directly and indirectly through disturbances such as fire (Flannigan et al., 2000), drought (Howden et al., 2003), introduced species (Simberloff, 2000), insect and pathogen outbreaks (Ayres and Lombardero, 2000), hurricanes (Loope and Giambelluca, 1998), wind storms (Peterson, 2000) and ice storms (Irland, 2000) (Dale et al., 2000). Impacts can be seen across an array of spatial scales, from the leaf to the forest landscape, and can include a reduction in leaf function, deformed tree structure, tree death, altered regeneration patterns through the destruction of seed banks, a disruption in the physical environment from soil erosion and nutrient loss, and increased patchiness of forest communities (Dale et al., 2000). Because trees survive for long periods of time and take many years to become established, many climate change impacts on forests will be expressed through alterations in disturbance regimes (Franklin et al., 1991; Dale et al., 2000; Dale et al., 2001).

Other indirect effects of climate change on forests are often difficult to detect due to the complex and interdependent nature of ecosystem components. Yet, many indirect effects are just as serious if not more so than some direct effects, due to the cascading nature of the relationships (Hansen et al., 2001). For example, an alteration of the timing of flowering and fruiting caused by temperature changes can have a relatively minor impact upon the plant species, but the cascading effects on animal species dependent upon the fruit could be substantial (Bazazz, 1998). Likewise, changes in precipitation patterns caused by climate change will likely cause greater conversion of intact forest areas as some agricultural lands experience drought and erosion.

The impacts on forests from elevated levels of atmospheric CO_2 have been studied, though the results are “neither clear nor conclusive” (NRC, 2002; Gitay et al., 2001). Higher concentrations of CO_2 generally improve efficiency of water use as plants open their stomata less and thereby reduce water loss through transpiration, though disparate results for overall plant growth have been shown, depending on the species, individual tree age, and length of study period (NRC, 2002). Moreover, plants have been shown to adjust to higher CO_2 levels such that the higher absorption rates can decrease over time (Gitay et al., 2001). Difficulties of modeling the effects of elevated CO_2 concentrations are compounded when other anthropogenic emissions are considered. For example, ozone (O_3) offsets potential benefits of CO_2 on plant productivity (Karnosky et al., 1999; Isebrands et al., 2001); while nitrogen oxides may enhance forest growth in nitrogen-limited systems (Robinson et al., 2002).

Within the next 50-100 years, changes to ecosystem functions and plant demographic processes will be the imminent threats, though in the long term, large shifts in forest types are likely to occur (Hilbert et al., 2001). Looking broadly at forest types, boreal forests are expected to be impacted severely through a reduction in extent since warming will be greatest at the poles (IPCC, 2001). In the tropics, the impacts of sea-level rise are predicted to be significant for mangroves as they are inundated in many areas (IPCC, 2001). In tropical forests more generally, the effects of drought and changes in seasonality will compound existing threats of fragmentation and degradation. Across all forest types, some of the most vulnerable will be island or relict forest communities, including highly fragmented forests surrounded by agricultural or urban development and forest systems on remote islands whose migration opportunities are hindered either latitudinally or altitudinally, as in the case with tropical montane cloud forests (Dudley, 1998). Individual species especially vulnerable are those with limited geographical ranges with low rates of germination or survival of seedlings and those with limited seed dispersal or other migration capabilities (IPCC, 2001). Those species inhabiting the boundaries of heat or drought tolerant limits may be especially at risk. More detailed information on the extent of impacts for each major forest type is outlined below.

Dudley (1998) provides an overview of major categories of changes expected in forest ecosystems:

DISTURBANCE: climate change will increase the degree of disturbance, through extreme weather events such as storms and as a result of smaller but ultimately more pervasive changes to seasonality, rainfall and temperature. Climate change will thus add to those other forms of human disturbance, which are currently fragmenting and altering forest ecosystems.

SIMPLIFICATION: the net effects of problems with tree reproduction and species' migration rates in areas experiencing severe climate change will tend to cause problems for slower growing species and instead favour fast growing, short-lived weed and invasive species. The result will be an acceleration of a trend that is already occurring as a result of other forms of human interference, namely, the replacement of species-rich forests by species-poor forests.

MOVEMENT: is likely both geographically and altitudinally, as growing conditions alter. The ability of trees to migrate fast enough to keep pace with climate change is still largely unknown and will depend upon many other factors. The extent to which ecological conditions change will depend on a complex mixture of factors: for example, warmer conditions could encourage trees to move up-slope while accompanying droughts might have the reverse effect.

AGE REDUCTION: disturbance, increased forest fires, changes in pest patterns and the transition of whole communities will encourage an existing trend towards the replacement of old-growth forests with younger stands. This has particularly important implications for biodiversity, as many of today's threatened species are those confined to older habitats.

EXTINCTION OR EXTIRPATION: some of the most vulnerable forest habitats, including relict species at the edge of their ecological niche and some particularly threatened systems, such as mangroves on low-lying islands, could disappear altogether. Species could also disappear from some forests that appear to be surviving the changes relatively well.

CLIMATE CHANGE IMPACTS ON TROPICAL MOIST FORESTS

Although warming will be greatest at the poles, the impacts of climate change on tropical forests can still be substantial due to their relative sensitivity to climatic variables. Phenological processes are highly correlated with climatic signals. Any changes in climate can have significant impacts on a forest ecosystem. Changes in plant phenology are said to be the most immediate indicators of climate change (Corlett and LaFrankie, 1998). Related to this are the coevolutionary relationships that are highly specialized and could become disrupted if a species is affected by a changed phenological event or physiologically (Bazzaz, 1998).

Perhaps most importantly, high species diversity per unit area in tropical moist forests creates narrow niches that may be severely impacted by a reduction in biodiversity through elimination of species when migration to other suitable habitats is not an option (Bazzaz, 1998).

The sensitivity of hydrological regimes in tropical forests due to existing levels of deforestation could be exacerbated through a change in structure and function, particularly in low-lying areas where floods may increase in frequency and intensity (Bonell, 1998). The predicted decline in the rainfall in the Amazon Basin and the intensification of the Indian monsoon will have large-scale effects on availability of water for tropical forests (Bazzaz, 1998).

The frequency and intensity of fire are likely to increase due to climate change in tropical moist forests, where fire is naturally rare or nonexistent. The interrelationships of fire, climate and forest ecology are complex, and will depend upon a particular forest type. However, in some places, an increase in drought could cause desiccation of forest that could spur more fires. Alternatively, increased precipitation results in more biomass which provides a larger fuel load that in turn makes forests that are already vulnerable—due to framentation and other human-induced threats—more susceptible to large-scale fire events. Most tropical moist forests are not resistant to fires, which could cause a large-scale loss of biodiversity. These forests will experience a change in species composition increasingly favoring xeromorphic, pyrophytic and generally species-poor plant communities that create a positive feedback as the new ecosystem will be increasingly liable to burn. Extreme cases would result in desertification. (Dudley, 1998; Goldammer and Price, 1998)

At a course level, distributional shifts in forest types have been predicted for a number of tropical forest regions using Global Circulation Models that focus on temperature and precipitation changes. A 1 °C rise in temperature would increase the productivity of rainforests as a whole as long as all other factors are held constant. However, changes in rainfall patterns combined with warming can produce sizeable shifts in the distribution of forest types. Increased rainfall enhances growth of tropical moist forests (holding fire, pests, and the effects of other factors constant), while decreased precipitation could shift existing tropical moist forests to favor woodlands and tropical dry forests. (Hilbert, in press). Several of the member countries to the United Nations Framework Convention on Climate Change within the tropics have conducted an analysis of expected distributional changes in forest types. For example, the composition of forest types in Thailand is estimated to change dramatically, with subtropical forests declining and tropical forests in the southern region of the country increasing due to increases in precipitation combined with an increase in temperature (OEPP, 2000). In general, many shifts in distribution are expected to take place at the edges of forest types and in ecotonal areas between rainforest and more open forest areas (Hilbert, 2001).

TROPICAL MONTANE CLOUD FORESTS

Tropical Montane Cloud Forests (TCMF) are an important subset of moist tropical forests from a climate change perspective. Even small-scale shifts in temperature and precipitation are expected to have serious consequences for tropical forests in the high mountains; indeed, many of the impacts have already caused species extinctions. TCMFs are especially vulnerable because they reside in areas with steep gradients associated with their ecosystem boundaries where the climatic conditions are highly specific and therefore catered to endemic biota. Atmospheric warming is raising the altitude of cloud cover that provides TCMF species with moisture via predictable and prolonged immersion in clouds (Pounds et al., 1999). The habitat for TCMF species will shift up the slopes of mountains as they follow the retreating cloud base, forcing populations of reptiles and other species into an increasingly smaller area.

The extreme sensitivity of the microclimates of TCMFs to climate change make a good case for using these systems as a ‘listening post’ for detecting climate change (Loope et al., 1998). Several examples exist around the globe. In the highland rainforests of Monteverde, Costa Rica, the lifting of the cloud base associated with increased ocean temperatures has been linked to the disappearance of 20 species of frogs. (Pounds et al., 1999). The Wet Tropics World Heritage Area of northeastern Queensland in Australia provides another example of highland tropical habitat whose complex topography has resulted in highly specialized ‘cool islands’ housing extremely rare fauna that will be threatened by a warmer, drier local climate in the next few decades (Hilbert, 2001). A doubled CO_2 scenario will shift relative humidity up-slope by hundreds of meters during the winter dry season when forests are most reliant on moisture from clouds. With only one degree of warming, the highland rainforest habitat in this area could decrease the amount of habitat by as much as half, causing one-third of endemics to decrease. It is entirely probably that 30-50 species and most highland faunal species will disappear with average temperature increases of 1-5 °C (Hilbert et al., 2001). Yet another example exists in East Maui, Hawaii, where the steep microclimatic gradients in montane tropical forests, combined with increases in interannual variability in precipitation and hurricanes are expected to produce a situation where endemic biota will likely be displaced by non-native plants and animals (Loope et al., 1998).

CLIMATE CHANGE IMPACTS ON TROPICAL DRY FORESTS

The bulk of reported and predicted impacts of climate change on tropical dry forests concern the desiccation and related fire risk of this forest type. A simulation using the

Holdridge Classification Model integrated with GCMs under a doubling of CO_2 in the next century for Tanzania shows that a decline in precipitation and increase in ambient temperature will produce a shift from subtropical dry forest and subtropical moist forest to tropical very dry forest, tropical dry forest, and small areas of tropical moist forests. Predictions of increased disease and predation of seeds and seedlings are expected to cause a change in species composition and structure in the Kitulandgalo Forest Reserve as some species will fail to establish themselves. (Mwakifwamba and Mwakasonda, 2001) In Thailand, subtropical dry forest that currently covers little over one percent of the country's total forest area may disappear entirely as it is replaced by tropical dry forests and tropical very dry forest emerging in the north and northeast of the country (OEPP, 2000).

A change in the precipitation, either through an annual increase or decrease is expected to make tropical dry forests subject to greater risk from forest fires in the immediate term. For areas where precipitation is expected to decrease, thus prolonging the dry seasons, increased desiccation makes the forest system more likely to ignite. Reduction of Net Primary Productivity (NPP) combined with the growing impacts of grazing and farming, however, will lead to a landscape which is more sparse and unable to support the spread of fires. In areas that are predicted to experience enhanced precipitation, an increase in plant biomass will lead to a more continuous source of fuel to support more frequent and intense fires. However, a trend of increased fire occurrence tends to lead eventually to a general decrease of fires due to the reduction of fuelbeds over time. (Goldammer and Price, 1998)

CLIMATE CHANGE IMPACTS ON TEMPERATE FORESTS

The effects of climate change are already apparent in temperate forests such as in the United States and Canada, where a 1-2 °C increase in ambient air temperature and changes in precipitation have been documented for the past century (Watson et al., 1998). Forest decline and dieback along the Atlantic and Pacific coasts are thought to be related to increased levels of CO_2 (Mueller-Dombois, 1992). A further increase in ambient air temperature is expected to shift the range of suitable habitat for temperate forests northward – in the case of the United States, between 100 to 530 km during the next century (Iverson et al., 1999; Iverson and Prasad, 2001). Assuming a 2 °C warming over the same time period, tree species will be forced to migrate at a rate of approximately 1-3 miles per year, which is much too rapid for the bulk of temperate species, except for those whose migration is aided by birds carrying their seeds. In general, a shift in species composition to more heat-tolerant 'fast adapters', even grasslands, is likely (NAST, 2001). Indeed, species associated with human-dominated landscapes as well as exotics which are more tolerant to climatic extremes have already greatly expanded their ranges in the United States (Drake et al., 1989; Flather et al., 1999).

Flora and fauna inhabiting temperate forests will be affected physiologically, as well as through a loss of habitat and an increase in extreme weather events such as droughts, floods, windstorms, and wildfires that could increase tree mortality. As forests shift, they will become increasingly vulnerable to additional disturbances, such as diseases and other pests, as well as to fires as natural species regimes are altered (NAST, 2001). Warming can be particularly detrimental to many tree species when increased temperature speeds up the development of insects and pathogens, and thereby increases rates of infestations (Hansen et al., 2001). Increased desiccation in fragmented temperate forests, such as those in the Bassit upland and the Jebel Saheiliyeh in Syria may be seriously threatened through an increase in wildfires (Dudley, 1998).

Some models predict an overall increase in forest productivity with increased temperature, though other climatic-induced disturbances may counteract this. In addition, increases in productivity of one system may have negative effects in linked systems. For example, increases in forest productivity in the Great Plains could decrease the availability of water to aquatic ecosystems such as the Mississippi River intercoastal waterways. (NAST, 2001)

The National Assessment Synthesis Team (NAST) of the U.S. Global Change Research Program finds that a vast degree of biodiversity change is expected in the United States (NAST, 2001). The maple/beech/birch forests currently present in the Appalachian Range from New England and as far south as West Virginia and western Pennsylvania could disappear. The aspen and birch forests in the Upper Great Lakes region could be lost, while patches of red spruce forest communities may become extinct in its present range. Assuming a gradual warming, these forests will likely be replaced by oak/pine and oak/hickory forests, though a significant total loss of forest cover may occur if warming is more extreme and coupled with increased droughts, wildfires and/or insect infestations. An increase in the total area of forests burned could be on the order of 25-50% as increases in productivity create larger fuel loads that spark fires when coupled with more intense periodic droughts. (NAST, 2001; Howden et al., 2003). Some predict that warming in cooler areas such as in the northern United States and western mountains near the Canadian border will increase tree richness (Currie, 2001) and benefit reptiles and amphibians; though a quarter overall decrease in bird and mammal richness is also predicted, especially in the eastern U.S. (NAST, 2001; Hansen et al., 2001).

Similar trends are predicted for temperate forests in Scandinavia, where Norway spruce and beech are expected to move north and possibly replace other forest communities such as those with dwarf birch. Likewise, in China, cold temperate coniferous forests and mixed temperate coniferous and boreal forests will likely be reduced (Dudley, 1998). A comparative analysis of vegetation distribution in the Montseny mountains of Catalonia in northeastern Spain over the last half century shows a replacement of cold-temperate forests with Mediterranean forests that is correlated with warming combined with the cessation of traditional land management. Beech *(Fagus sylvatica)* and heather *(Calluna vulgaris)* are being replaced by holm oak *(Quercus ilex)* forest at mid-altitudes (800-1400 m), which has resulted in isolation and degradation of beech communities through its shift upwards in altitude. Within the isolated beech stands, the trees are more defoliated (by 30%), recruitment is 41% lower, and holm oak recruitment is three times higher than in more stable and continuous beech stands. (Peñuelas and Boada, 2003)

CLIMATE CHANGE IMPACTS ON BOREAL FORESTS

Warming is being felt more at the poles, with an expected rise of 4-5 °C during winter that may go as high as 10 °C over the next century according to some models (Sekula, 2000). The overall effect of this warming will affect the species composition and other ecological services of two-thirds of boreal forests (Kirschbaum and Fischlin, 1996), and cause a dramatic loss of between 25% and 40% of boreal forest area, as gains in the north are unable to keep up with replacement by temperate species in the south (Stone, 1996). Boreal forests will be replaced at lower latitudes by temperate forest species, grasslands, and in Russia, forest-steppe. Boreal forest habitat is predicted to migrate poleward by 300-500 km in the next century (IPCC, 1996b). In Russia, a reduction in boreal forests on the order of 19% and loss of productivity is predicted through General Circulation Models (Krankina et al. 1997). Plant hardiness zones have already shifted in accordance with warming over the last century in Canada, most notably in the western part of the country (McKenney et al., 2001).

Migration will be inhibited to a great extent, however, by inhospitable tundra soils and lack of biota that is necessary for colonization. The rate of colonization by tree species differs greatly, depending on the seed dispersal rate and range of tolerance, for example with white spruce colonizing at 100-200 km/100 years, and 4-8 km/century for Scots pine (IPCC, 1996b). An average rate of 25 km/century through seed dispersal and propagule establishment (Solomon, 1992) will mean that the rate of warming is likely to be approximately 10 times faster than that needed for successful species migration (Jardine, 1994). Moreover, tree species will be impeded from successful migration due to barriers such as habitat fragmentation and competition from more hardy exotic species (Iverson and Prasad, 2001; James, 2001; Collingham and Huntley, 2000).

Many tree species will also suffer physiological problems or changes in the timing and rate of seed production (Stewart et al., 1997) which will inhibit growth and reestablishment rates and in the long term, successful migration. Plants with narrow temperature tolerances, slow growth characteristics (Kirschbaum and Fischlin, 1997) and limited dispersal mechanisms (e.g. heavy seeds) will be the most vulnerable (Thompson et al., 1998). A new composition of species favoring early successional trees and shrubs over slow-growing woody species will be the net result (which will also entail a total loss of stored carbon). Further, a drastic change in species composition and loss of overall habitat with even 2 °C warming near the poles will cause a loss of ecosystem functionality as species richness is diminished. A decrease in habitat through this scenario would result in the loss of animals inhabiting the boreal Great Basin mountain ranges on the order of 10-50% (IPCC, 1996b).

An average rise in temperature of 1 °C over Canada in the last century has had an impact on plant physiology and phenology (NRC, 2002). At mid to high latitudes (45°N and 70°N), warming has corresponded with increased plant growth and the length of the growing season (Myneni et al., 1997). Warming that was accompanied by a decrease in precipitation has had a detrimental impact on plant growth in some tree species in western Canada such as aspen poplar, where reduced tree ring growth has been associated with drought events (Hogg et al., 2001). Reproductive timing in tree species has also been recorded, for example the trembling aspen in Alberta has begun blooming 26 days earlier over the last century (Beaubien and Freeland, 2000), and the bud break of white spruce in Ontario is also taking place earlier (Colombo, 1998).

Boreal forests are expected to become victims of increased insect infestations with the onset of warmer conditions. Many temperate pests such as the mountain pine beetle, normally limited by cold in boreal ranges, will expand their range, and many boreal tree species will be ill-equipped to deal with their infiltration, especially if ecosystem health is already compromised. At the same time, local boreal pests will be given longer periods to flourish under warmer winters. (Stewart et al., 1997; Sekula, 2000) Fleming et al. (2001) document historical trends that show that spruce budworm outbreaks increase the frequency of wildfires by increasing the amount of dead plant matter that serves as fuel for fires.

Warmer and drier conditions will also lead to changes in hydrological regimes, and have large-scale impacts through more frequent, severe, and widespread forest fires. Climate will be the underlying cause of ecosystem change via fire, which is the major disturbance regime in the boreal ecosystem. Studies have shown that fire frequency as well as the total area burned has increased in the last 20 to 40 years in accordance with warmer temperatures (Schindler, 1998; Kasischke et al., 1999; Stocks et al., 2000). A longer fire season, drier conditions and an increase in lightning storms are projected to increase the fire season severity in accordance with climate change (Stocks et al., 1998; Goldammer and Price, 1998). An initial increase in fires will aid the migration of fire-adapted species to germinate, as well as providing nutrients to the soil. However, over time, increased fragmentation due to fire will inhibit chances for migration. The result will be a shift of age class distributions toward younger forests (and a decrease in stored carbon).

CLIMATE CHANGE IMPACTS ON MEDITERRANEAN FORESTS

Hulme and Sheard (1999) provide an overview of the most notable effects of a warming and drying trend in the Mediterranean region, including a decrease in water availability and a corresponding increase in fires, both of which will have significant impacts upon regional biodiversity. Increased dessication brought on by climate change will further compound a trend towards reductions in groundwater supplies due to intensification of farming and urbanization. In the Iberian Peninsula (Spain and Portugal), the annual mean temperature has risen by nearly 1.6 °C over the last century, where the warmest years occurred in 1989, 1995 and 1997. Precipitation is expected to decrease by an average of 5-15% annually. Winters are expected to get wetter while the other seasons are expected to become drier, especially summer. Fires, while a natural component to the ecosystem, are becoming increasingly threatening, and an increase in occurrence and area burned is strongly correlated with increasing daily maximum temperature and decreasing humidity. In 1994, a fire burned almost half a million hectares of Spanish forest and shrubland and killed 31 people. A loss of Mediterranean woodland habitat will have a noted impact upon the endangered Iberian lynx due to a reduction in two of its vital food sources—rabbit and duck.

CLIMATE CHANGE IMPACTS ON MANGROVES

The principal climate change-induced threat to mangroves comes from sea-level rise. Floods in the East African coastal region point to high vulnerability in this region (IPCC, 2001). In Bangladesh and India, the biodiversity of the Sunderbans is at great risk due to rising seas; a one meter rise in sea level will likely cause the Sunderbans and the tiger with it to disappear (IPCC, 2001).

Rising sea-levels bring about changes in sediment dynamics, erosion and changes in salinity, all of which could compromise the ability of a mangrove system to survive. Many communities will be inundated while others will suffer from changes to hydrological and salinity regimes. Inundation has been shown to bring about a decrease in photosynthesis and increase salinity and salt stress during floods in the Everglades National Park in Florida (Dudley, 1998). Moreover, sea level rise is expected to take place at about twice the rate at which sediment build-up—necessary for the mangrove's survival—will occur and cause the sinking of many deltas. Lastly, "erosion will reduce the size of mangroves, by cliff erosion on the seaward edge that undercuts mangrove roots, through sheet erosion across the swamp surface and by cutting away of tidal creek banks" (Dudley, 1998).

Canvass and Assess Adaptation Options

After completing a vulnerability analysis to determine how a forest system may be impacted by changing climatic conditions, the next step is to look at the range of adaptation options available in order to promote resiliency. An effective vulnerability analysis will determine which components of the system—species or functions, for example—will be most vulnerable to change, together with consideration of which parts of the system are crucial for ecosystem health. An array of options pertinent to adapting forests to climate change are available, both to apply to forest communities at high risk from climate change impacts as well as for those whose protection should be prioritized given existing resiliency. Long-term adaptation of species will be enabled where natural adaptation processes such as migration, selection, and change in structure are allowed to take place due to sufficient connectivity and habitat size within the landscape.

Forest adaptation options are not dissimilar from traditional forest conservation methods; however great emphasis is placed upon increasing spatial and temporal scales, protection of key forest communities, managing specifically for increased disturbances, and flexibility given uncertainties and surprises surrounding what climate change will bring. The menu of options below all seek to maintain the health of forest biodiversity as the overarching vehicle for successful adaptation. Criteria for sustainable forest management outlined in the Montreal Process of the United Nations Conference on Environment and Development include maintenance of forest ecosystem health, conservation of biodiversity, maintenance of forest productivity, and conservation of soil and water resources (MPWG, 1998). Sustainable forest management criteria provide a framework into which adaptation strategies can be incorporated (NRC, 2002).

1. REDUCE PRESENT THREATS

The most apparent strategy for improving forest resilience to climate change is to promote overall ecosystem health. As discussed earlier, a variety of present non-climate threats to forest systems exist, namely conversion, fragmentation, and degradation. Identifying and targeting for action the reduction of priority threats in a particular forest system will go far in ensuring that forest structure, composition, and function that increase a forest's resilience are maintained.

2. AVOID FRAGMENTATION AND PROVIDE CONNECTIVITY

Noss (2000) provides an overview of the negative effects of ecosystem fragmentation which are abundantly documented worldwide. "Edge effects" threaten the microclimate and stability of a forest as the ratio of edge to interior habitat increases. Eventually, the ability of a forest to withstand debilitating impacts is broken. Fragmentation of forest ecosystems also contributes to a loss of biodiversity as exotic, weedy species with high dispersal capacities are favored and many native species are inhibited by isolation.

The importance of minimizing road networks deserves special consideration. Roads exacerbate the effect of a warmer climate to increase the incidence and rate of invasions of forests by pest and disease by encouraging the dispersal of invasive exotic species. They also restrict the dispersal of less mobile native species.

3. MAXIMIZE SIZE OF MANAGEMENT UNITS—DECISION-MAKING ON A LARGE, BIOGEOGRAPHIC SCALE

The fossil record provides evidence that species have adapted to changing climates by shifting their ranges. Protected areas established to conserve a particular species may not contain appropriate habitat in the next few decades. Overlaying a climate change scenario upon existing protected areas and other management units will give managers an indication of where a given habitat will occur to enable revision of management boundaries. However, given the rather crude estimation of climate change impacts within particular locales as well as the largely unknown change in ecosystem dynamics that will occur, it is prudent to give forest systems the maximum allowance of habitat in which to migrate (Noss, 2000). Attention should be given in the design of protected area networks to the need for north-south as well as altitudinal migration opportunities. The solution in this case does not rely solely on a reorientation of protected area boundaries, but also to a paradigm shift where decision-making regarding land uses takes place on a large, biogeographic scale to include potential habitat outside reserves (Hilbert, In Press).

4. PROVIDE BUFFER ZONES AND FLEXIBILITY OF LAND USES

The fixed boundaries of protected areas are not well suited to a dynamic environment unless individual areas are extremely large. With changing climate, buffer zones might provide suitable conditions for shifting of populations to lands border-ing reserves as conditions inside reserves become unsuitable (Noss, 2000). Buffer zones increase the patch size of the interior of the protected area and overlapping buffers provide migratory possibilities for some species (Sekula, 2000). Buffer zones must be large, and managers of protected areas and surrounding lands must demonstrate considerable flexibility by adjusting land management activities across the landscape in response to changing habitat suitability. A specific case for a buffer zone surrounding tropical montane cloud forests can be made based on research that shows the upwind effects to deforestation of lowland forests causes a raising of the cloud base (Lawton et al., 2001).

5. REPRESENT FOREST TYPES ACROSS ENVIRONMENTAL GRADIENTS
Representing the full range of habitat types is a traditional conservation method, to set aside areas for scientific study, as a node of comparison against disturbed areas, and as a means of conserving species that may be too difficult to manage separately. The uncertainty about the precise type and distribution of impacts necessitates maintaining a full spectrum of forest types within protected areas to enable some resistant and resilient types to persist. (Noss 2000)

6. PROTECT MATURE FOREST STANDS
Primary forests have been shown to be particularly resilient to climate change (Franklin et al., 1991). Mature trees are better able to weather large-scale disturbances than recently established forests (Brubaker, 1986), thereby providing a refuge for species reproduction once favorable climatic conditions return (Noss, 2000). While shifts in composition along environmental gradients are still expected in established forests (Franklin et al., 1991), the effects are expected to be much slower, thereby giving species more time to adapt.

7. PROTECT FUNCTIONAL GROUPS AND KEYSTONE SPECIES
Maintaining the natural diversity of species and functional groups in forests is a sound overall strategy for enhancing both resistance and resilience to climate change. Several recent studies have demonstrated increased tolerance to environmental extremes and recovery potential as species richness increases. Species diversity in turn promotes the “redundancy” or number of species present in critical functional groups. Functional groups include various kinds of producers, pollinators, seed dispersers, predators, parasites, decomposers, and so on. Thus, it is not just species diversity that matters, but also species composition. Both may enhance the stability of a forest ecosystem. Efforts to identify keystone species and functional groups will help forest managers maintain natural patterns of abundance and distribution. (Noss, 2000)

8. PROTECT CLIMATIC REFUGIA
“Across continents, at both temperate and tropical latitudes, topographically diverse areas allowed habitats and lineages to persist through altitudinal shifts and, in many

cases, to diverge during periods of climate change" (Noss, 2000). Climatic refugia are important for maintaining assemblages of species typical of past climates. Identifying and protecting areas will decrease the non-climate stresses species in these places may be under to enhance their chances for survival so that they may function as refugia during future climate change. In North America, such areas include the southern Appalachians, the valleys of major rivers in the southeastern coastal plain of North America, and the Klamath-Siskiyou region of northwestern California and southwestern Oregon. Major refugia in Europe include Iberia, Italy, the Balkans, and the Caucasus. In Central America, riparian habitats have been important refugia, especially along the Caribbean coast. (Noss, 2000)

9. MAINTAIN NATURAL FIRE REGIMES

The frequency and intensity of fires are known to correlate with changing climatic conditions. However, the relationships of fire to a particular forest ecosystem, and the different management decisions that are required vary greatly for different systems. Fire suppression has actually been shown to bring about a decrease in biodiversity in some areas where fire is a natural component of the ecosystem (Noss et al., 1995; Noss and Peters, 1995), while in other areas, particularly in the tropics, human-set fires have had catastrophic consequences for biodiversity (Trapnell, 1959; Van Schaik and Kramer, 1997; Dudley, 1998). Noss (2000) provides an overview of the complexity of fire management for different forest ecosystems, and provides some general guidelines. "Regional differences in fire ecology imply that fire policies established in response to concerns about climate change should not be uniform; rather, they should be established based on what is known of the fire ecology of each region and forest type…A mixed strategy in which managers let many natural fires burn, protect old growth from stand-replacing fires, and manage other stands through prescribed burning and understory thinning, is probably the optimal approach" (Noss, 2000). Some high value smaller areas may require protection from fire (Stocks et al., 1998). For example, Hirsch et al. (2001) promote the integration of 'fire-smart landscapes' that reduce the intensity and spread of wildfire and its impacts through harvesting, regeneration and stand tending.

10. ACTIVELY MANAGE PESTS

Climate change has been associated with increased infestations of insects, disease, and exotic species (Williams and Liebhold, 1995). This has been abundantly documented in cooler climates, where increases in temperature and decreases in precipitation have led to increases in attacks by spruce budworm in boreal forests, for example (Fleming et al., 2001). In ecosystems where pests are predicted to have a significant impact on the system, an active management program to reduce the negative effects of the pest could be devised (Howden et al., 2003). Prescribed burning is an option for reducing vulnerability to pest outbreaks in some temperate and boreal regions (Wheaton, 2001). Nonchemical pesticides have been proposed as means to reduce leaf mortality from insects (Johnson, 2001). Other nonchemical options such as baculoviruses are being investigated for their potential use in attacking pest species such as spruce budworm while leaving other species and the environment relatively unharmed (NRC, 2001).

11. SILVICULTURAL TECHNIQUES TO PROMOTE FOREST PRODUCTIVITY

Because climate change will likely have differential impacts upon different species and age classes of trees, a straightforward, 'no regrets' strategy is to apply silvicultural techniques that maintain a diversity of age stands and mix of species (Krankina et al., 1997). These measures will contribute to maintaining the productivity of the forest system as climate changes. Other silvicultural activities, such as collecting salvage cuttings from ice storms, may reduce the amount of long-term damage arising from future storms (Irland, 2000).

12. PREVENT CONVERSION TO PLANTATIONS AND PRACTICE LOW-INTENSITY FORESTRY

Forestry operations that minimize soil disturbance and utilize less clearcutting and chemical pollutants help reduce the invasion of exotic species, loss of carbon from soil, and the potential loss of mycorrhizae. The size of canopy openings and removal of biomass from sites should both be reduced. These methods are more likely to promote the resistance and resilience of forests to climate change than intensive forestry operations. (Noss, 2000)

13. MAINTAIN GENETIC DIVERSITY AND PROMOTE ECOSYSTEM HEALTH VIA RESTORATION

Adaptation to climate change via selection of resilient species depends upon genetic variation. Efforts to maintain genetic diversity should be applied, particularly in degraded landscapes or within populations of commercially important trees (where genetic diversity is often low due to selective harvesting). In such places where genetic diversity has been reduced, restoration, especially using seed sources from lower elevations or latitudes, can play a vital role in maintaining ecosystem resilience (Noss, 2000). Hogg and Schwarz (1997) suggest that assisted regeneration could be used in southern boreal forests in Canada where drier conditions may decrease natural regeneration of conifer species. Similarly, genotypes of beach pine forests in British Columbia may need assistance in redistributing across the landscape in order to maintain long-term productivity (Rehfeldt et al., 1999). In addition, species can be specifically selected for replanting that are known to be more resilient to impacts in a given landscape. For example, trees with thick bark can be planted in areas prone to fire to increase tree survival during increased frequency and severity of fires (Dale et al., 2000).

14. ASSIST MIGRATION WITH SPECIES INTRODUCTIONS TO NEW AREAS

Management programs specially designed for tree species that will be especially impacted by climate change may be necessary in some areas. The primary method of ensuring the species' survival will be to consider introducing the species that are 'climatologically trapped' to more suitable or safe habitats (Sekula, 2000). This may take placed outside the species' present range, though new areas may become more appropriate for the species under new climatic conditions. Dore et al. (2000) suggest that careful introduction of selected tree species in the Boreal Transition Ecozone may prove more ecologically and economically viable than current forms of agriculture. In all cases, special attention should be given to the species' history and potential effects of its introduction (PSRS, 2003), and the reintroduction should be well planned and coordinated with other management programs (Sekula, 2000).

15. PROTECT MOST HIGHLY THREATENED SPECIES *EX SITU*
For some forest ecosystems, such as the cloud forests of tropical mountains, climate change is already (or will soon become) the dominant threat to an extent that mitigation efforts will not prevent some loss of species. In these situations, *ex situ* preservation of species in zoos and botanical gardens may be the only way to avoid extinction. Collections should include sufficient genetic diversity to allow adaptation to uncertain conditions in reintroduction sites. (Noss, 2000)

For the Great Plains island forests in North America, Henderson et al. (in press) recommend a "discovery, provenance and breeding program, encompassing both extant tree species within island forest and possible new species introductions, with the objective of establishing which varieties and species are best adapted to the range of probable future climates in island forests" (Henderson et al., in press). Specific measures could include: "collection of seed from dry microsites within and outside island forests, determination of related tree species to those now extant which might add resiliency, use of plantation trial sites within or adjacent to island forests or outside where such sites might serve as analogues for future moisture conditions at island forest sites" (Henderson et al., in press).

Identify and Select Adaptation Strategies

The selection of adaptation strategies will depend largely upon the existing and eminent non-climate stresses to the forest system, that is, the baseline upon which climate change will exert additional pressure. The overlay of climate-induced threats pointing to particular species or system vulnerabilities will aid in the choice of strategies. For example, in areas where forests are degraded due to species extraction, such as within many mangroves, reforestation of mangal species in accordance with knowledge of future changes to the hydrological system are likely to be the most obvious preventative measure to increase the chances for survival during the onset of sea-level rise.

Once managers are armed with knowledge of non-climate and climate threats to a system, it will be important to develop a vision for what the management plan is trying to achieve. As Millar notes (PSRS, 2003), the goal should not be to stop change or preserve a species, population or landscape in its current or former condition. Especially for highly vulnerable systems, "change may be inevitable, and resisting it could lead to abrupt and undesired consequences in the future" (PSRS, 2003). Forest composition and distribution that occurred before large-scale settlement (the 1800s) developed in response to the harshest period of the Little Ice Age which ended in the late 19th century, and are probably not good models for climate change in the present and future (PSRS, 2003).

As noted above, making forests more resilient to climate change necessitates a multi-pronged approach targeting both forests at high risk as well as prioritizing protection for those that contribute significant genetic potential through their existing resiliency. Determining which category a particular forest community fits within will help managers choose from the suite of adaptation options.

The first basic strategy for all forests should be preventative measures, such as protection through the creation of national parks, reserves, or buffer zones. There are 44,000 protected areas worldwide, covering an area equivalent to China and India combined. However, this constitutes only about 12% of the world's forests having legal protection of one sort or another since the dawn of the modern conservation movement in the late 1800s. WWF's Forests for Life campaign estimated that in 1996 only about 6% of the world's forests were formally set aside for strict protection purposes. Moreover, many of the existing protected areas are protected in name only, and are seriously degraded or under pressure from illegal logging, poaching, mining and other threats.

Where some category of protection—strict or otherwise—does not appear likely, avoiding fragmentation through the minimization of road networks, and practicing low-intensity forestry are sound options. Preventing damage that will compromise a system's resilience to climate change is usually much less costly than actions to restore it.

For forests at high risk to climate change, a range of strategies to deal with known disturbances are possible. As a prevention measure, one approach is to manage for the disturbance, for example by decreasing the density of tree planting to reduce susceptibility to drought, or removing trees vulnerable to ice or wind storms. Other disturbances, including fires, and pests can also be managed through preventive measures and thereby manipulate the intensity or frequency of the disturbance. Another approach is to mitigate the forest disturbance itself. This can be done, for example, by limiting the introduction of non-native species or by using prescribed burns. Forests can also be manipulated with the aim of reducing vulnerability after the disturbance has occurred. Recovery efforts can be employed after the disturbance or managed in an ongoing process, for example for adding structural elements that create shade for the reestablishment of vegetation, or through the planting of late successional species to speed up succession. Short-term mitigation efforts will be necessary in some instances in order to support certain gene pools until a stable habitat is identified. (NAST, 2001)

When choosing among adaptation strategies, managers will be increasingly challenged to view the role that climate change plays in perpetuating human-related changing conditions within forests. This realization will necessitate a fresh examination of threats such as overgrazing, invasive species, or fires in light of the role that climate change plays. (PSRS, 2003).

Lastly, the importance of decision-making for ecological change on a large biogeographical scale that incorporates socio-economic and development priorities can not be stressed enough. Adaptation strategies that may be deemed necessary within a small forest community could change once placed upon a larger ecological landscape. Consideration of competing priorities—both among conservationists and through the larger human and development landscape—will create a more realistic management plan with better chances for success.

Implement or Recommend Actions and/or Policies

Once a vulnerability analysis has been conducted, and adaptation strategies chosen, it is necessary to decide how the actions will be implemented. Forest managers for a given system will likely be aware of existing management plans, and it is important to take stock of how the adaptation strategy would fit with these plans. If no clear management plans exist, it is conceivable to produce one focusing specifically on increasing resilience to climate change. Ideally, adaptation management strategies in response to climate change will serve as another layer in a comprehensive forest management plan that has as its objective the overall health of the forest ecosystem. For example, many WWF ecoregional visions are adding vulnerability to climate change as another component that will drive conservation decisions. Such anticipatory adaptation plans take climate change into account during the planning process (NRC, 2002), and will better ensure synergies with other management priorities. It is also usually much less costly to adjust management practices in advance of future changes rather than to wait for evidence of large-scale damage.

A number of scientific, governmental and NGO institutions are acquiring expertise in the area of climate change impacts and adaptation. It will be fruitful to seek partnerships with these institutions at the beginning of any project to analyze climate impacts and options to increase resilience. The United Nations Environment Program is implementing a new program which is being jointly executed by the System for Analysis Research and Training (START) and the Third World Academy of Sciences (TWAS), with funding from the U.N. Global Environment Facility called “Assessments of Impacts and Adaptations to Climate Change (AIACC)”. The aim of this project is to “enhance the scientific capacity of developing countries to assess climate change vulnerabilities and adaptation, and generate and communicate information useful for adaptation planning and action” (AIACC website, 2003). For boreal systems, Environment Canada, the federal environmental agency, founded in 1999 the Science, Impacts and Adaptation Project with $15 million in funding to better understand risks from climate change and formulate responses (Environment Canada, 2003). The Potsdam Institute for Climate Impact Research in Germany includes in its mission to contain human-induced climate change to a tolerable level, and provide suitable measures to adapt to the unavoidable warming of the planet, particularly in the poorest developing countries (Potsdam Institute website, 2003). Likewise, a number of research institutes within universities have sprung up in the last several years to study forest vulnerability to climate change and adaptation.

Partner institutions and other stakeholders—especially those that will be impacted by any management decisions—can assist in the implementation of adaptation plans. A critical component of any adaptation project will be to devise a rigorous and goal-oriented monitoring system for the given management area and surrounding landscape to the extent possible in order to detect whether management techniques are having the desired effect. Monitoring is also important given the relative uncertainty with which climate change will change forest systems, especially via the complex relationships between species structure, composition, and functioning. Many monitoring programs exist for fire, insects or pathogens, but few exist to monitor reserve areas or for other disturbance events such as landslides or ice storms (NAST, 2001). The results of monitoring will also enable lessons to be drawn from adaptation management efforts, and to compare these with similar 'control' landscapes or other adaptation projects in different regions with similar habitat type. These lessons could be disseminated through reports, websites, and other educational materials.

Examples of Existing Adaptation Strategies

The United Nations Environment Programme's World Conservation Monitoring Centre (WCMC) has begun a project called "Forests in Flux" with the goal to define priority areas for networks of forest protected areas across the globe. A crucial component of the project is "review[ing] and assess[ing] predicted responses of forest ecosystems to climate change, focusing specifically on key issues for conservation, particularly ecosystem tolerance and loss of biodiversity" (WCMC, 2003). An 'ecosystem response (forests and climate change) database" has been established through the project in order to assess current knowledge of predicted responses of forest ecosystems through summaries of model specifications, parameters, nature of predictions, references and a listing of collaborators. Ecosystems identified as highly vulnerable have been flagged for more detailed analysis.

The AIACC initiative mentioned above includes a number of on-going adaptation projects relevant to the forest sector in developing countries. For example:

A project in Southern Africa is "developing more realistic ways of predicting the response of plant, animal, bird and reptile species to a changing climate in the presence of a changing and fragmented landscape. The project will analyze a range of adaptation options to determine which are the most effective, cost-efficient, and robust" (AIACC South Africa project website, 2003).

In Malawi, Zambia, Zimbabwe, and Mozambique, a project is being carried out to "assess vulnerability and explore adaptation options to climate variability and extreme events in the Miombo region…that lie within the drainage basin of the Zambezi River" (AIACC Miombo project website, 2003). The project is developing datasets and scenarios of land use change, a regional integrated model, and tools for analyzing regional impacts and adaptation, including a case study documenting climate—land use—people—ecosystem linkages in order to guide adaptation plans.

A project in Southeast Asia is analyzing "the impacts of climate change and associated land use and cover change on water resources, forest ecosystems, and social systems of watersheds…" (AIACC Southeast Asia project website, 2003).

In China, climate change impacts and possible adaptation strategies for key sectors are being determined through an integrated approach, including workshops, surveys, multi-stakeholder consultations, ecological modeling, GIS and remote sensing, and multi-criteria decision-making. (AIACC China project website, 2003).

The adaptation strategies suggested above will be key measures in the short and medium term to maximizing the resilience of forest systems impacted by climate change. Even if emissions were drastically reduced today, human-induced changes in temperature and precipiation will cause wide-ranging disturbances upon ecosystems within the next century, due to the long lifespan of emissions in the atmosphere. Therefore, the only long-term option to ensuring healthy forest ecosystems is to reduce emissions of greenhouse gases now so that we will not leave a legacy of forests fraught with problems far worse than those reviewed here.

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