FORESTS AND CLIMATE CHANGE
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EXECUTIVE SUMMARY

Climate change and forests

Global change poses enormous challenges to those responsible for managing the world's forests. There is perhaps no other ecosystem that is so closely linked to, and affected by, human induced changes to climate - being regarded simultaneously as a victim, a villain and a potential saviour.

Concentrations of carbon dioxide methane and other greenhouse gases are rising at an accelerating rate in the atmosphere, largely as a result of emissions from human activities such as the burning of fossil fuels. This increased air pollution is thought to be having a dramatic impact on climate, both by raising average global temperatures and by increasing extreme events such as droughts and storms. The current global warming trend is agreed by scientists to be at least partially the result of increasing human induced emissions of greenhouse gases to the atmosphere. Forests will both suffer from these changes and, when managed badly, can themselves be the cause of some climate change through carbon dioxide released during forest fires and deforestation. However, forest management is now also increasingly seen as potential way of helping to halt or even reverse climate change, adding further confusion to what was already a complex situation.

Currently, up to a fifth of greenhouse gases are thought to come from biomass burning, both through accidental fires and, increasingly, as a result of the use of fire for land clearance or to cover up illegal activities such as logging in protected areas. The 1997 and 1998 fires in Asia and the Amazon have focused global attention onto this issue. A positive feedback develops, where biomass burning contributes to climate change, which itself increases the likelihood of further fires and so on. The recent and extreme El Niño climatic event is an indication of the type of conditions that are likely to become commoner in the future (and El Niño may itself have been increased in intensity and frequency by climate change).

How climate change can damage forests
Perhaps even more importantly, climate change itself has a range of known and predicted impacts on forests throughout the world. In recent years, our understanding about these phenomena has increased enormously. A range of more complex and sometimes contradictory hypotheses has superseded early predictions and field data have been used to back up theoretical studies. New research has extended our understanding to a greater number of forest ecosystems.

Several problems have been identified. Climate change can destabilise forests, both stimulating and sometimes depressing growth. Changes in temperature will alter a tree's ability to survive, and may "move" optimal conditions for ecosystems, geographically or to different altitudes, faster than trees can follow through natural dispersal. Temperature-related changes such as increased evapotranspiration can directly threaten forest ecosystems, particularly when they are at the edge of their ecological tolerance. Warmer conditions will also increase some pests and diseases. A rise in number and severity of droughts will have particularly acute impacts in some tropical systems, both by killing trees through water shortages and by increasing forest fires. Changes in seasonality may upset tree’s reproductive strategies. Sea-level rise could inundate many mangrove forests, particularly on islands and flooding may damage riparian communities. Other forms of human interference exacerbate problems from climate change, and it is clear that where ecosystems are already under threat from human disturbance, fragmentation or development pressure, climate change is likely to have a significantly greater impact than on undisturbed, healthy ecosystems. In that sense, climate change may turn out to be the "straw that breaks the camel's back" for some forest species and habitats.

At least a third of the world's forests are likely to be affected by climate change. There will be a trend towards unstable, younger and simpler forests with reduced biodiversity. Some forest boundaries will move geographically, if suitable conditions exist and migration is not blocked by agriculture or by other human developments. Species extinctions are likely to occur both in relict or sensitive communities or even in more apparently stable forest ecosystems.

Forest particularly at risk include:

- **Boreal forests**, where predicted climate change effects are greatest. Research has thrown up many different models of impacts - ranging from increased growth due to warmer conditions to net losses through the effects of drought, fire and pests. There has been intense debate about the ability of trees to move their population fast enough to keep pace with changes in environmental conditions. Up to 40 per cent of the boreal forest could be lost altogether.

- **Tropical forests**, including particularly those that are sensitive to drought and increased drying trends, tropical storms, changes in rainfall pattern, seasonality and fire. Tropical forests that would not previously have burnt may be most at risk from climatic change, as they will not be adapted to fire. Risks are often increased by human disturbance and felling.

- **Mangroves**, in areas where sea level is expected to rise. Evidence from past temperature changes suggests that many mangrove systems will be unable to build up sediment fast enough to keep pace with sea-level rise and will thus be reduced in extent or even eliminated. Inundation and salt stress are particular problems.

- **Island and relict communities** in places with significant climate change. Risks are increased both because there is little room for migration and because a smaller gene pool reduces options for rapid adaptation. Yet islands have some of the highest levels of biodiversity and endemism,.

- **Replacement of other communities**: There is also the possibility that in some cases trees will invade other ecosystems, for example putting alpine meadow, tundra or savannah species at risk.

Risks from forest management

More recently, forests have also come under the spotlight because tree planting and forest conservation have been suggested as ways of offsetting greenhouse gas emissions, through various ways of gaining emission credits outlined in the United Nations Framework Convention on Climate Change (UNFCC). While in theory this could provide vital funds for forest conservation and sustainable management, the policy remains controversial and its scientific basis full of uncertainty. There is still little proof about how effective such measures would be in terms of mitigating climate change, serious concern about the long-term sustainability of projects, major problems with baseline data and monitoring and a near-certainty that forest sequestration will not be as effective as reducing emissions at source. There is also some evidence that they might encourage bad forestry practice - in extreme cases including the replacement of natural forests with fast growing plantations of exotic species. There is a serious concern amongst many environmentalists that as currently drafted, the

Kyoto Protocol of the UNFCCC may actually embed perverse incentives that would lead to loss of forest quality and diversity if implemented.

Addressing the problems

The only real way to reduce the impact of climate change is by taking early action to reduce pollution at source. However, in the medium term, some steps may be taken at a regional level to mitigate expected impacts of climate change. Although the science of conservation under conditions of climate change is still in its infancy, these steps are likely to include maintaining natural forest corridors and "stepping stones" to facilitate migration and in some cases active management to for example suppress fires in drought-stricken forests. The more resilient and un-fragmented a forest is, the more likely it is to be able to adapt to climate change.

PREFACE

Five years ago, WWF published a book on the implications of climate change for global biodiversity. Although *Some Like It Hot*[1] drew on the experience of many specialists around the world, it was inevitably speculative in places, because only limited research had been carried out. This new report revisits one particular issue identified in the earlier book – the potential threats that climate change poses for natural forests around the world – discusses some new research and looks at how opinions and have changed in the years since publication.

Perhaps the most significant change is the growing agreement about the question of whether climate change is really happening at all – and here there has been a clear and probably decisive shift in political and scientific opinion. While governments argue about who should do what to address the problems, there is now a broad consensus that the problems really do exist and this has general fresh impetus to the questions of how to tackle climate change problems.

There is also a general understanding that it will be a long time before we know exactly what is happening and how it will play out for forests. Indeed, given the scale of other changes that humans have imposed on the world's forests, it may never be possible to separate human induced climate change from natural changes in the climate. In this context, the broad conclusions that WWF reached in 1993 remain relevant:

> *Impacts on forest ecosystems will vary greatly from one place to another. In many cases, stable, mature forests may well be quite robust in the face of climate change. However, once these are disturbed, through logging, fire, pollution or other factors, re-establishment may become much more difficult, as seedling stages are generally amongst the most sensitive*[2].

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INTRODUCTION

Forests: Victims, villains or saviours?

Global climate change poses enormous challenges to those responsible for managing and living in the world's forests. There is perhaps no other ecosystem that is so closely linked to, and affected by, human-induced changes to climate - being regarded simultaneously as a victim, a villain and a potential saviour

Increasing emissions of greenhouse gases such as carbon dioxide and methane appear to be having a dramatic impact on climate, both by raising average temperatures and by increasing extreme weather events such as droughts and storms. Forests are likely to be substantially affected by these changes, as a result of both direct impacts on tree health and indirect impacts from changing pest and disease patterns and from extreme climatic events. In addition, badly managed forests can be the *cause* of climate change as a result of carbon dioxide released during forest fires or land clearance. And adding further confusion to what was already a complex situation, forest management is now also increasingly seen as potential way of helping to *halt or even reverse* climate change through forest management aimed specifically at carbon sequestration and storage. All these issues have relevance to forest conservation. The current paper focuses on the first – the impacts that climate change is having, or is likely to have, on forests. A short résumé of the other main issues is given at the end of the document.

PART 1

Climate change – from speculation to science

Over the past decade, initial and general predictions of climate change have increasingly been replaced by a more robust science, leading to an increasing consensus among researchers. This has been demonstrated most clearly in the successive reports of the Intergovernmental Panel on Climate Change (IPCC), the international scientific advisory body charged with developing an overview on the issues for the UN Framework Convention on Climate Change. Emission of greenhouse gases from fossil fuels, burning biomass, intensive farming and some industrial processes are contributing to changing weather patterns. These changes include a rise in average annual temperature and an increase in extreme events such as droughts and storms. Both rainfall and drought are likely to increase in places and average sea level will probably rise. The world is apparently entering a period of warmer, less predictable climate. The IPCC is uncharacteristically blunt in its assertions about the implications for forests: *Forests are highly sensitive to climate change*[3]

Historical and palaeoecological studies show that past climate changes, for example, after the ice ages, had dramatic impacts on ecosystems and that trees can have problems in moving fast enough to keep pace with changing ecological conditions. Pollen records and the existence of relict communities, such as the tropical rainforest fragments found in the middle of the Australian desert, bear witness to large-scale changes in the past. Yet past climate changes were almost certainly less abrupt and less extreme than those changes now being predicted to occur n the near future. They were also acting on far less fragmented and damaged ecosystems. Sustained increased in average annual temperatures of as little as $1^{o}C$ is sufficient to cause changes in the growth and regeneration capacity of many tree species, leading to changes and losses in forest cover. Although warmer conditions can stimulate growth, they also increase many stresses and pressures on tree species and ecosystems. The net effect is likely to be a loss rather than a gain.

PART 2

Increasing complexity

In response to the growing consensus about climate change threats to forests, there has been a rapid growth in research effort. The theoretical studies of a few years ago, based upon early models of climate change and forest dynamics, have been followed up by more sophisticated analyses and increasingly also by field measurements. A new generation of specialist scientists has developed. Climate ecologists have reached back to data from past research on anomalous weather conditions and used these, along with a developing expertise in climate modelling, to develop what is in effect a new field of predictive ecology. During the 1990s, four broad developments in our understanding have taken place:

- Early and simplistic predictions about impacts of climate change on forests have been replaced by a range of more subtle, complex and in some cases contradictory analyses –the sheer complexity of likely vegetation responses has also been recognised;

- Research has expanded to new geographical areas, such as tropical rainforests, which had previously been largely ignored in climate studies;

- Evidence has emerged of current, measurable changes in forest ecosystems that follow the patterns predicted to result from climate change; and

- There has been a realisation that apparently unconnected events, such as forest fires and pest attack, may be linked back directly or indirectly to climate change.

The result is an understanding that is both broader and to some extent more cautious. Many uncertainties still exist. Nonetheless, a large range of possible responses has been identified, and these are discussed below.

PART 3

A variety of responses to climate change

Climate change will affect forest ecosystems in a number of ways. The most commonly predicted impacts are as a result of increased temperature and changes in rainfall and humidity. Other possible factors include changes in drought, greater storm frequency, higher wind speeds, increased fire incidence, possible carbon dioxide (CO_2) fertilisation and secondary effects such as changes in the pattern of pest and disease attack. Some of these (for example higher temperatures and CO_2 fertilisation) could increase growth while others (pests and fires) will tend to depress growth.

Some effects may partially cancel each other out; for example increased temperatures will increase rates of water use, but this may be offset to some extent in some forests because CO_2 can increase efficiency of water use.

Increases in carbon dioxide levels: are generally assumed to have a fertilising effect on trees, particularly when combined with higher temperatures and/or rainfall. For example, elevated carbon dioxide levels have been shown to increase productivity and efficiency of water use due to reduced stomatal conductance[4]. Some studies claim to have found evidence of this effect already, although measurements of five tree species in the Sierra Nevada failed to find significant correlation with CO_2[5]. Indeed, carbon dioxide fertilisation remains a controversial topic and some researchers believe that a range of feedback loops reduce the overall impact. For example, in Finland it has been found that elevated CO_2 levels increased early photosynthesis but also caused earlier cessation of growth so that net effects were equivocal[6]. Despite firm evidence of increases in CO_2 during this century, clear evidence of impacts on tree growth has not yet been found from tree ring surveys, or if present have been linked to other factors.

Increased temperature: will have an impact on growth rates, location of optimum habitat and on many related issues such as fires, drought and pests (see below). Higher temperatures generally increase rate of growth, but can also sometimes depress growth by increasing evapotranspiration and thus water stress. Temperature changes could lead to a retreat in permafrost in the boreal region, an increased tendency to drought in the tropics and dry forest areas, and to a longer growing season in many parts of the world. The geographic distribution of species will change (often to a higher altitude or latitude) and ecosystems will be disrupted and in some cases could disappear altogether. Isolated species, high montane forest and island habitats such as those of the Pacific islands will be especially at risk. Higher temperatures may have detrimental impacts on trees as well, and raised winter temperatures have been associated with increased needle loss and reduced growth in the Scandinavian boreal forest[7]. Impacts in the tropics are harder to predict. For example, flowering and fruiting in many species are closely linked to temperature, so that changes could destabilise species with narrow ecological niches[8]. In a feedback that could further affect climate, warmer temperatures may also increase rates of soil organic matter decomposition, thus increasing levels of CO_2.

A key factor in determining how well trees will adapt to temperature changes is their ability to *migrate* across a landscape – to follow optimal climatic conditions. Research in North America, studying evidence of changes during warming periods 10,000 and 13,000 years ago, suggested that migration rates could be an order of magnitude lower than that needed to keep pace with predicted changes, although some researchers believe this to be overly pessimistic[9]. In general, wind dispersed seeds migrate approximately twice as fast as those spread by animals. Pollen moves faster than seeds, so that movement of genes within a species' range (and hence ability to adapt to changing conditions) may be better able to keep pace with the rate of climate change than situations where a whole ecosystem moves geographically.

Migration will also be affected by other related factors such as the presence of competitors, local environmental conditions and – perhaps most of all - by human activities[10]. It is likely to be fraught with problems, particularly for slower growing tree species, because dispersal will not only have to be rapid, but will take place through uncertain and variable conditions where important factors – such as symbiotic fungi, correct germination temperatures etc – may be absent.

Changes in seasonal patterns: are related to temperature and could be a decisive factor, particularly in some tropical and Mediterranean climates. Both increases and decreases in the length of the dry season have been predicted in different parts of the world. Current research suggests that an increase in dry season is probably the most significant impact and relates to issues of water shortages and forest fires as discussed below. However, changes in seasonality could also have major implications for trees or other forest species with a highly specialised ecology related to day-length or other seasonal triggers. This has been suggested, for example, as an important problem in terms of reproductive success in the tropics, particularly related to seedling establishment[11].

Water shortages: can result directly from longer dry seasons, but can also occur because of higher evapotranspiration rates under warmer conditions, even if seasonality if unaffected. While many tree species have compensatory mechanisms to allow them to survive occasional temperature fluctuations, such as leaf shedding, long-term changes could influence forest succession. For example, there may be a tendency for tropical evergreen forests to be replaced by semi-deciduous forests[12]. This in turn could lead to a loss of biodiversity. Research suggests that 26-39 per cent of trees in wetter parts of Panama are not found where it is drier, and that a 9-week extension of the dry season in very wet regions could cause 40 per cent of species to become extirpated[13].

As so often, different climate-related changes can partially or completely cancel each other out. For example, a study on the effects of climate change on plant herbivore interaction in moist tropical forests found that higher CO_2 levels tended to increase the productivity while drought had the opposite effect – the latter being judged dominant in this case[14].

Increases in forest fires: have been related to climate change, although the links are complex. Drought can both increase and decrease fire risk in different conditions: in the first place by drying the forest and secondly by reducing growth and thus the presence of combustible material. Increased rainfall also has opposite impacts that can in varying conditions cause both a decrease and an increase in the threats of fires through increasing water content and increasing growth and thus the amount of fuel available. Today, risks of fire are also often increased by greater human pressure.

Research suggests that in many parts of the world the net result will be an increase in fire frequency. For example, research in northern Minnesota showed that forest fires were most frequent in the warm and dry periods of the fifteenth and sixteenth centuries[15] and increased fire intensity has been linked to drought years in the European Mediterranean countries[16]. Research in Canada suggests that a doubling of atmospheric CO_2 would lead to a 46 per cent increase in seasonal severity rating for forest fires, and possibly a similar increase for their incidence[17].

Threats from fires have assumed new levels of importance following some catastrophic fire events during the late 1990s. In 1997 and 1998, during an extended drought related to the periodic climatic event known as El Niño, fires swept through millions of hectares of Indonesia, Malaysia, Papua New Guinea, Brazil, Colombia, Australia, many African countries, the USA and Mediterranean Europe. Many started as a result of deliberate burning, but swept out of control as a result of weather conditions. They created enormous human health problems, economic costs and threats to endangered species such as the orang utan (*Pongo pygmaeus*) in Borneo[18].

Although forest fires are a natural part of the ecology in some forests, today they are also frequently burning in tropical moist forests where they would, under natural conditions, be rare or absent. Fires are also affecting forest fragments and relicts that are unable to absorb the impacts of large-scale fire events. Such fires change the ecology, leading to an increase in species-poor xerophytic and pyrophytic habitats, as is currently occurring in parts of the Amazon. This itself creates a positive feedback, because the new ecosystems are themselves more liable to burn, leading in extreme cases to desertification[19]. The fires can cause enormous damage to forest structure and to the associated biodiversity when they burn in forests that are not naturally fire-prone. For example, in the first of the massive Indonesian forest fires in 1983, Kutai National Park in Borneo was virtually destroyed[20].

Changes in pest and disease incidence: could also have direct impacts on trees. Warmer conditions could increase the incidence of pests or allow pest species to reach higher latitudes or altitudes; indeed in theory currently benign species could expand to become new pests. In Finland, for example, the European sawfly (*Neodiprion sertifer)* is predicted to increase due to warmer conditions[21]. In Alaska, warmer conditions have led to a series of dramatic and unprecedented infestations of spruce bark beetle over up to 20 million hectares of forest, which it is suggested are early field indications of climate change problems for the temperate forests of the far north[22]. Such problems are increased by the tendency for invasive species to be introduced with timber imports or through other forms of escape.

Increases in hurricanes and storms: rising sea surface temperatures are expected to increase both the intensity and frequency of hurricanes and cyclones[23]. Periodic wind disturbance in the cyclone belt is one of the key natural factors influencing forest structure and dynamics. For example, a dry evergreen forest in Sri Lanka lost 40 per cent of its trees in a hurricane and in 1978, Hurricane Joan flattened 80 per cent of the forest in parts of eastern Nicaragua. Research in Puerto Rico shows that while some species, such as *tabonuco* (*Dacryodes excelsa*), are adapted to survive hurricanes, overall diversity is depressed by increased intensity and frequency of hurricanes. If hurricane frequency doubles as predicted, tree mortality could increase by around 50 per cent and the surviving forest will be poorer in species, with fast growing and short-lived weed species becoming more common. Commercially important timber species such as *tabonuco*, *Sloanea berteriana* and *Manilkara bidentata*, are likely to decline[24].

Sea-level rise is the perhaps the best understood of all possible global warming impacts, with particularly significance for mangroves and coastal forest communities. Research suggests that while mangroves could theoretically accommodate about 8-9 cm/century sea level rise, predicted changes are almost an order of magnitude greater. Mangroves will be unable to build up sediment fast enough to keep pace with rising water, and may also suffer problems from salinity changes, erosion, reduced photosynthesis and increased storms**.** Erosion will reduce the size of mangroves, by undercutting mangrove roots, through sheet erosion across the swamp surface, and by cutting away of tidal creek. Inundation may cause direct stress to trees through reduction of photosynthesis. Sea level rise is also likely to cause increased salinity, and thus salt stress, for example in the Florida Everglades[25].

Other forms of human interference: also play a critical role in whether and to what extent forests will decline under conditions of climate change. This is a critical point that still all-too-often is missed out of climate research. Many – perhaps most – of the world's forests have suffered a decline in ecological quality as a result of human activities. These include deforestation, logging, fuelwood collection, intensive forest management, agricultural expansion, replacement of mangroves with shrimp farms, mineral mining, oil drilling, road building, release of acidic and other pollutants and changes in the water table[26]. Many of the world's forests are already under stress. This means that climate change impacts are both an *additional* set of stresses and that forests are less able to accommodate these because of other factors. For example, humans caused most of the fires that swept the world's forests in 1997 and 1998, but climate change may have increased the *severity* and *frequency* of these fires.

Many of these factors can act on a forest at any one time; in some cases all the stresses listed above can be present simultaneously. Some of them will tend to cancel each other out, while others can act synergistically to produce an impact greater than their individual parts. Research over the last five years has tended to add to our understanding about the degree of complexity. In the following section, and attempt is made to state in general terms what the results might be for forests in general and for some forest ecosystems in particular.

PART 4

Responses in different forest ecosystems

All forest types are potentially liable to experience impacts under conditions of climate change, although the degree of the response will change with ecology and location. Despite the variability amongst climate change models, there appears to be a growing consensus that, under the most likely scenarios, *around a third of the world's forest areas will be significantly affected*. The types of changes to be expected vary to a great extent with location.

Several trends can be identified:

- **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, that is 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.

All these changes can themselves form a positive feedback that would create further changes in the forest and/or exacerbate climate change. For example, any serious decline during a transition period, when forest ecosystems are moving or altering their composition or structure, could result in a further pulse of CO_2 being released.

One important net result is that further losses of biodiversity are likely, particularly amongst endemic species with limited distribution, on islands or amongst those species with very precise ecological niches.

In the following section, six broad categories of forest are discussed in more detail:

- Boreal forests
- Temperate forests
- Tropical moist forests
- Tropical dry and Mediterranean forests
- Mangroves
- Isolated and fragmented forests[1]

[1] This is not a forest type. However, responses to climate changes in fragmented or isolated forests (including those found on remote islands) are distinctive enough to justify discussing them separately.

Boreal forests: contain some of the largest remaining areas of more-or-less primary forest in the world. Under most climate change scenarios, they are also the most seriously affected forest ecosystem, with up to two thirds of the total area likely to be affected. Some estimates suggest that 25-40 per cent of the boreal forests could disappear altogether, being replaced by temperate forests or tundra[27]. However, there is considerable disagreement about the scope and direction of changes. A special conference of the International Boreal Forest Research Association in 1995 produced many different opinions about whether the boreal forest would be a net winner or loser, although the final statement suggested that it would be likely to suffer a decline[28].

Boreal forests are likely to be particularly affected by increases in potential evapotranspiration demands, which could dry soils and increase fire risks[29], increased fires and pest attack and by changes in the permafrost. Most models suggest that the boreal forest zone will move to the north. For example, a recent study of the impact of climate change on the Siberian tiger in the Russian Far East found that there would be a northward shift in natural ecotones, with an increase in boreal forest and a decrease in tundra. Core areas for the tigers would decline, with replacement uncertain because of agricultural expansion[30]. Some field research suggests that these changes may already be occurring. There is for instance already evidence of melting of permafrost in parts of Canada, which would allow the forest to spread to higher latitudes[31].

As with other ecosystems, boreal forests are likely to undergo a simplification of biodiversity in the future. Research in the Lake Superior National Forest, USA, suggested that white birch, balsam fir and quaking aspen forests could be replaced by sugar maple (*Acer saccharum*) by 2010[32].

Early models suggested that warmer temperatures and CO_2 fertilisation could lead to increased rates of growth, but these predictions have been rejected by other studies. For example, an interdisciplinary study in the MacKenzie River Basin in Canada found that a combination of factors, including increased fires, pest attacks by white pine beetle and other species, and drought-related die-back reduced overall productivity[33]. A recent overview of scenarios[34] found most predictions suggesting that drought-related die-back could occur fairly shortly after warming occurred, although some models suggest an initial burst of growth followed by later declines. Studies of tree growth rates throughout the boreal region suggest that the initial burst in growth may already be underway[35]

Temperate forests: are also considered likely to undergo significant changes under predictions in many climate models, although changes are thought likely to be less extreme than for the other forest systems discussed. Temperate forests may invade other ecosystems, including evergreen tropical and boreal forests, wet maritime areas and alpine meadows. For example, predictions suggest that subalpine forest could replace meadows in parts of the US Olympic National Park[36]. In other cases, declines are likely. Impacts will stem from warmer temperatures, changes in water availability, increased CO_2 levels and changes in pests and diseases. Although net productivity may increase, increased decomposition of soil organic matter in warmer soil conditions may offset any additional carbon storage. Although temperate forests are currently a net carbon sink, as they re-grow following past deforestation, this may change if significant areas start to decline.

Predictions in the US Pacific Northwest suggest that the natural range of some tree species could move 500-1000 metres upwards, and the range of some species is are also predicted to shift north by several hundred kilometres. Further east, species such as yellow birch (*Betula alleghaniensis*) and sugar maple (*Acer saccharum*) could also move north by 500-1000 kilometres under a doubling of CO_2[37]. In Scandinavia, Norway spruce (*Picea abies*) will retreat from the south and beech (*Fagus sylvatica*), will increasingly move north possibly replacing dwarf birch (*Betula nana*) to some extent through competition[38]. In China, there could be losses of cold temperate coniferous forests and mixed temperate coniferous and boreal forests, with corresponding increases in tropical and monsoon forest, although models are complex[39]. In New Zealand, trees could theoretically move southwards although prior fragmentation makes this difficult and for example the range of the kauri (*Agathis australis*), could be drastically reduced[40].

Conditions may be particularly serious in arid regions at the edge of the Temperate Zone, where overgrazing, desertification and fuel-wood collection have already fragmented and degraded forest communities. In Israel, for example, it has been suggested that trees in the Mount Meron nature reserve could suffer from a combination of reduced predictability of February-April rains, plus higher summer temperatures. Desiccation of woody plants could destabilise the whole system and lead to more generally arid conditions. In Syria, increased forest fires might threaten the two remaining large areas of native forest, in the Bassit upland and in Jebel Saheiliyeh[41].

Tropical moist forests: are threatened more as a result of direct human degradation and deforestation than by climate change, although the latter is likely to increase the severity of the other impacts. Soil-water changes and the impact of extreme weather events are believed to be the most important factors[42] although changes in cloud cover may also be important. Tropical moist forests are likely to experience on average a slight temperature rise and increased rainfall, although local conditions will vary greatly and models are still crude[43]. Altitudinal zones are likely to move upwards[44]. There is also some evidence for increased frequency and severity of ENSO, the El Niño Southern Oscillation, as a result of climate change. El Niño is a periodic climatic disturbance that increases rainfall seasonality and can lead to severe and catastrophic droughts; it was a major factor behind the 1997 and 1998 fire events.

Disturbance from storms and cyclones may increase, while reproductive capacity amongst trees and other species may be reduced due to changing climatic conditions. If the dry season is reduced, many trees do not flower and fruit, leading to famine amongst fruit-eating animals. The impacts of such a drought were recorded in Barro Colorado Island, Panama, in 1970, and resulted in the death of animals such as armadillos and howler monkeys[45].

Increased cloud cover in some areas could reduce photosynthesis and thus productivity. On the other hand, *reduction* in cloud cover could *increase* water stress in other areas, particularly in cloud forests where moisture is obtained largely through occult precipitation or “fog-stripping”. For example, in Xishuangbanna forest in China's Yunnan province, loss of fog poses a threat to moisture-loving epiphytic orchids, ferns and mosses. Conversion to a drier climate, probably as a result of deforestation in neighbouring areas, has already led to a loss of 37 per cent of the original tree species in one area, thus illustrating conditions that may be more common in the future[46]. In Hawaii, steep gradients in cloud forests make species migration particularly difficult[47]. Although the greatest threats to tropical forest biodiversity come from direct human intervention, climate change is likely to increase these losses[48], both by simplifying the forest overall and by reducing the number of local and endemic species.

Tropical dry forests: are likely to be affected most by drought and fire, but predictions vary dramatically; for example two different models of vegetation responses (IMAGE/TVM and MAPSS respectively) have tropical dry forests having losses as high as 50 per cent or gains of up to 22.2 per cent[49]. Soil water availability will be a particularly important in areas where trees are already under stress and prolonged drought could lead to accelerating desertification, although separately global climate changes from human impacts may be difficult.

Mangroves: play a key role in maintaining coastal systems and water purity, and also provide breeding grounds for many shallow water fish; their disappearance undermines the livelihoods of local fishing communities[50]. They are already highly threatened as a result of land-use changes, for example through the development of shrimp farming or because of felling for charcoal production. They grow best on sheltered shorelines with plentiful sediment and where salinity is modified by freshwater. Mangroves have also been identified as amongst the most highly threatened forest communities under climate change conditions. For example, New Zealand mangrove communities are predicted to decline under several scenarios and communities on low-lying islands are also at risk[51]. It is suggested that mangroves of coral coasts and low islands are probably the most sensitive to climate change, followed by (in descending order) coastal lagoons, composite alluvial plains, tidal plains, alluvial plans and lastly drowned bedrock coasts[52].

The principal threat to mangroves comes from sea-level rise and the associated changes in sediment dynamics, erosion and salinity. Some communities will literally be inundated while others will be damaged by a combination of stress factors. Other potential problems arise from changes in rainfall, increased storms and possibly the impact of ultra-violet radiation[53]. Inundation may cause direct stress to trees through reduction of photosynthesis and increasing salinity and salt stress. These effects have already been observed in places where mangroves have been temporarily impounded as part of mosquito control programmes and through observations of flood events in the Everglades national park in Florida[54].

Stratigraphic studies of responses to rapid sea-level rise during the Holocene period show that many of today's mangrove ecosystems are unlikely to adapt fast enough to survive predicted sea level changes. Sediment levels will not build up quickly enough to keep pace with rising water – which is currently predicted to be almost an order of magnitude faster than adaptation time - leading to losses in vulnerable systems. 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. An increase in tidal range may also cause problems in some places. In delta systems such as the Sundarbans in Bangladesh, impacts of sea-level rise may be further intensified. Many deltas are sinking due to reduced sedimentation caused by water extraction and dam projects upstream.

Mangroves may be affected by other climate changes as well, including temperate and CO_2 rise, both of which might increase diversity in some systems. Any significant drying out of mangroves would be highly damaging and drought in Senegal and the Gambia has in the past led to decreases in mangrove communities. Increased storm damage may cause further problems in some areas.

Island and relict forest communities: will be particularly at risk for a number of reasons: they are likely to include species that have narrow niche limitations; can be relatively more affected by extreme weather events such as storms; and often have very limited options for migration. For example, island montane tropical forests have been identified as one of the habitats most threatened by climate change.

Fragmented communities pose particular problems. A recent review[55] identifies three stages of fragmentation: an overall *loss* of habitat; reduction in the *size* of remaining blocks; and increased *isolation* of habitats are new land uses occupy the intervening environment. Fragmentation often leads to species loss at both the level of habitat and landscape, and can also result in changes in faunal composition and ecological processes. Climate change can therefore increase threats to biodiversity already set in train by fragmentation. This is why many scientists regard current climate change as a far greater threat to species numbers than past climatic fluctuations.

Conclusions: in all cases, predictions are uncertain and reactions will alter according to local conditions. In general, climate change will create an additional stress to forests that are already suffering severely as a result of other forms of human disturbance. However, climate change is of additional importance because it respects no boundaries – and for example protected areas are also at risk. A recent study carried out for WWF showed that climate change could affect many protected areas in North America[56] and threats have also been identified to existing protected areas in many countries[57].

PART 5

Other issues related to forests and climate change

Forests are also of relevance to the climate change debate for several reasons:

- Forests can act as a net **emitter** of carbon if the amount of carbon released during breakdown of plant material exceeds that captured from the atmosphere during photosynthesis;

- Forests can act as **reservoirs** of carbon, both in above ground biomass and, more importantly, in soil humus;

- Forests can be **sinks** of carbon and there is currently much debate about options for managing forests in such a way as to increase carbon storage and this is now seen as a possible way of alleviating the effects of climate change.

Rapid release of carbon comes during periods of catastrophic change to the forest, most commonly during fires or mass deforestation although declines due to pest and disease epidemics, or even the impacts of climate change itself, can result in mass releases of carbon. In the latter case a vicious circle could develop, with climate change causing forest loss, causing further release of greenhouse gases and increased climate change. Over the last few years, around 20 per cent of the carbon released into the atmosphere has come from biomass, and large-scale burning in Amazon and the island of Borneo has been identified as a particularly important source[58]. (Note however that these sources are still dwarfed by burning fossil fuels.)

More recently, forests establishment and conservation have been promoted as ways of offsetting greenhouse gas emissions, through various forms of emissions credits outlined in the 1998 Kyoto Protocol of the Framework Convention on Climate Change, including Joint Implementation and the Clean Development Mechanisms. While in theory this could help reforestation projects and provide useful funds for forest conservation, the whole approach remains controversial. There is still little proof about how effective such measures would be in terms of mitigating climate change and a near-certainty that they will not be as effective as reducing emissions at source. There is also some evidence that they might encourage bad forestry practice - in extreme cases including the replacement of natural forests with fast growing plantations of exotic species. WWF has recently developed a policy position on this issue stating clearly the advantages and disadvantages of such an approach. In addition, a draft set of guidelines about when and how such schemes might be implemented is under discussion[59].

PART 6

Wrestling with the tiger – tackling climate change in forests

Although it has been said so often as to be virtually a mantra, it is worth repeating again that the only really effective way to tackle climate change is by addressing the problem at source, and reducing greenhouse emissions. The reluctance of some of the world's main emitters to address this issue lies at the heart of this growing problem.

However, given that current concentrations of greenhouse gases makes at least some climate change inevitable already is there anything that we can do to mitigate impacts in forests?

Jerry Franklin and others, reporting from the Pacific Northwest, point out that "forest management can either exacerbate or reduce the effects of climatic change on the productivity and biological diversity of northwest forestscapes"[60]. We have seen repeatedly in this report that unhealthy, low quality and fragmented forests are likely to be less able to withstand climate change than healthy, intact ecosystems. Although the science of climate change conservation approaches is still in its infancy, some clear indications already exist.

Amongst the most relevant for forests are:

- The need to maintain representative samples of healthy, intact ecosystems through ecologically-representative protected area networks, in order to protect the most resilient forest types.

- The importance of improving management outside protected areas. Commercially-managed forests or forests used for other purposes should maintain samples of natural habitat and as full a range of species as possible, to provide a safety net in case the designated protected areas can no longer support the type of forests they were established to preserve.

- Establishment of more effective environmental monitoring, to act as "early warning systems" of harmful changes.

- Development of greater understanding about and implementation of linking habitats such as "corridors" and "stepping stones" to facilitate migration in times of rapid climate change.

- Active protection and management of selected species or habitats highly threatened by climate change, such as particularly endangered animal species and habitats such as island mangroves.

- Development of protection strategies within community forest management projects, the operations of commercial timber companies and the approaches of state forest enterprises. Such an approach assumes considerable liaison work and partnerships between groups that may not have naturally worked together in the past.

- Maintenance of a diverse gene pool in forests, to facilitate rapid species evolution in time of climate change. This element is of relevance in a period in which increasing standardisation of commercial tree species is being promoted.

Such approaches will not "solve" the problems of climate change in forests, but they will provide a considered response that could help minimise losses.

PART 7

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