thought to have sequestered about 11.8 Gt C, with an annual sequestration rate of 0.2 Gt C year^{-1}. The IPCC has estimated that slowing the rate of deforestation combined with the promotion of natural forest regeneration and afforestation could increase terrestrial carbon stocks in the period 1995–2050 by between 60 and 87 Pg C. In Brazil alone, a reduction in the rate of deforestation by 50% could conserve as much as 125 Mt C year^{-1}.

A potentially much more valuable function of forests is as a supply of biomass for burning in power generation. While the carbon stored in the wood is immediately released into the atmosphere, the benefits are gained when the power that is generated replaces power generated from fossil fuels. This approach has been strongly advocated in some European countries, but there is still a need to look at the full costs of the power generation (i.e., including the carbon costs associated with the construction of the power generation plant and with the development and growth of the forest).

In addition to such direct methods, the IPCC has identified a number of silvicultural and management techniques that might be used to enhance carbon mitigation. These include fire prevention and control, protection against pests and disease, changes to rotation lengths, control of stand density, enhancement of nutrient supply, control of the water table, selection of useful species and genotypes, use of biotechnology, reduced regeneration delays, selection of harvesting methods such as reduced-impact logging, recovery of degraded forest, management of logging residues, recycling of wood products, increased use of wood, and efficiency of the conversion process from wood to products, and the establishment and maintenance of forest reserves. These methods all provide means by which the forest sector could contribute to the global effort to reduce anthropogenic impacts on the global carbon cycle.

See also: **Environment**: Impacts of Elevated CO_2 and Climate Change. **Mensuration**: Tree-Ring Analysis. **Nonwood Products**: Energy from Wood. **Tree Physiology**: A Whole Tree Perspective; Forests, Tree Physiology and Climate.

Further Reading

Aber JD and Melillo JM (1991) *Terrestrial Ecosystems*. Philadelphia, PA: WB Saunders.

Houghton JT, Ding Y, Griggs DJ, *et al*. (eds) (2001). *Climate Change 2001: The Scientific Basis*. Cambridge, UK: Cambridge University Press.

Karjalainen T (ed.) (2002) The role of boreal forests and forestry in the global carbon budget. *Forest Ecology and Management* 169(1–2), 1–175.

Kirschbaum MUF (2003) Can trees buy time? An assessment of the role of vegetation sinks as part of the global carbon cycle. *Climatic Change* 58: 47–71.

Metz B, Davidson O, Swart R, and Pan J (eds) (2001) *Climate Change 2001: Mitigation*. Cambridge, UK: Cambridge University Press.

Mohren GMJ, Kramer K, and Sabaté S (eds) (1997) *Impacts of Global Change on Tree Physiology and Forest Ecosystems*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Oberthür S and Ott HE (1999) *The Kyoto Protocol: International Climate Policy for the 21st Century*. Berlin, Germany: Springer-Verlag.

Schlesinger WH (1997) *Biogeochemistry: An Analysis of Global Change*. San Diego, CA: Academic Press.

Stocks BJ (ed.) (2002) The role of boreal forests and forestry in the global carbon budget. *Climatic Change* 55(1–2): 1–285.

Walker B and Steffen W (eds) (1996) *Global Change and Terrestrial Ecosystems*. International Geosphere-Biosphere Programme Series no. 2. Cambridge, UK: Cambridge University Press.

Watson RT, Noble IR, Bolin B, *et al*. (eds) (2000) *Land Use, Land-Use Change, and Forestry*. Cambridge, UK: Cambridge University Press.

Terminology

Pg C Petagrams of carbon (1 Pg C = 1 Gt C = 1000 Mt C = 10^{15} g C).

Tg C Teragrams of carbon (1 Tg C = 1 Mt C = 10^6 tonnes C = 10^{12} g C).

Mg C Megagrams of carbon (1 Mg C = 10^6 g C = 1 tonne C).

Gt C Gigatonnes of carbon (1 Gt C = 10^9 tonnes C = 3.7 Gt of carbon dioxide).

Mt C Megatonnes of carbon (1 Mt C = 10^6 tonnes C).

Impacts of Elevated CO_2 and Climate Change

G E Jackson and J Grace, Edinburgh University, Edinburgh, UK

© 2004, Elsevier Ltd. All Rights Reserved.

Introduction

Forests have always been sensitive indicators of climate change. Tree pollen, preserved in lake sediments and bogs, provides a record of how tree species migrated northwards as warming occurred after the retreat of ice about 12 000 years ago. Many tree species reached a maximum northern limit in the warm period (5000–8000 years ago) and then retreated in the somewhat cooler period that followed. On a shorter timescale, most trees leave a faithful record of their annual growth over their lifetime, as annual growth rings in their stems. For northern species there is an excellent relationship between temperature and annual growth. From such records scholars have been able to use ancient wood samples found in old buildings and bogs to reconstruct past climates.

Another indication of the sensitive response of temperate trees to climate comes from phenological gardens where the timing of bud break and leaf unfolding is observed every year. These records show that trees begin their growth earlier nowadays than they did 20 years ago, matching the rise in temperature.

In this article we examine the current rate of climate change, and the predictions that have been made about the future climate. We discuss how forests may be responding to the changing climate, bearing in mind that factors other than the climate are changing too. These factors include the rising carbon dioxide concentration and the rate at which nitrogen (as ammonium or nitrate) is deposited on the land surface.

Climate Changes

Since the end of the last glacial period some 12 000 years ago, the temperatures of the northern hemisphere have increased markedly. Of particular interest are the changes over the last 100 years, which have been unusually rapid. The Intergovernmental Panel on Climate Change (IPCC) has produced a series of reports, the latest of which (the Third Assessment Report) was produced in 2001. This comprises three volumes, the first of which, *Climate Change 2001: The Scientific Basis*, provides the most up-to-date and reliable assessment of the recent state of the global climate. It finds that the global average surface temperature has increased over the twentieth century by 0.6°C (±0.2°C) (**Figure 1**). It also states that globally the 1990s were almost certainly the warmest decade and 1998 the warmest year in the instrumental record.

The second main feature of climate change is an altered rainfall pattern across the globe. After temperature we may expect rainfall to have an important influence on the growth of forests. Over the twentieth century rainfall patterns have changed according to broad latitudinal bands. In most mid and high latitudes of the northern hemisphere continents it is very likely that precipitation has increased by 0.5% to 1% per decade. Over subtropical land areas in the northern hemisphere (10° N to 30° N) it is likely that rainfall has decreased during the twentieth century by about 0.3% per decade. Over the tropical land areas (10° N to 10° S) it is likely that rainfall has increased by 0.2–0.3% per decade, although, interestingly, little change has been found in this region over the past few decades. Over the southern hemisphere no comparable systematic changes have been found in broad latitudinal averages.

Further important changes in the climate which influence forests include changes in cloud cover and changes in extreme weather events, for example seasonal patterns of temperature, heavy precipitation events, storms, fire, snow cover, floods, and droughts. Changes in cloud cover are less certain than increases in temperature and altered rainfall patterns but it is likely that there has been a 2% increase in cloud cover over mid- to high-latitude land areas during the twentieth century. A further potential threat to global climate, which has only recently been appreciated, is the possible increase in frequency and severity of El Niño-Southern Oscillation (ENSO) events. El Niño occurs in the tropical Pacific Ocean and happens when warm water from the western Pacific flows toward the east. Warm surface water builds up off the coast of South America and the earth's atmosphere responds by producing patterns of high and low pressure that can have a profound impact on weather far away from the equatorial Pacific. El Niño is associated with a fluctuation in the circulation in the Indian and Pacific oceans called the Southern Oscillation. Modeling and observational studies suggest that ENSO events are associated with abrupt shifts in climate, which since ecological systems are particularly vulnerable to rapid changes may prove of greater consequence than the gradual changes in other climatic factors.

Reasons for the Climate Changes

The recent and rapid changes in climate are thought, in part, to be induced by human activity. Burning of fossil fuels and changes in land use, especially deforestation, have resulted in increased atmospheric greenhouse gas concentrations. The main greenhouse gases that have increased in the last 100 years are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). They have a warming effect on the earth by absorbing the longwave radiation being emitted from the earth that would otherwise escape to space and cool the planet. **Figure 2** shows the increase in greenhouse gases during the last millenium. Since 1750 the CO_2 concentrations in the atmosphere have increased by approximately 0.4% a year from 280 ppm to the present day concentrations of 367 ppm. Methane and nitrous oxide have

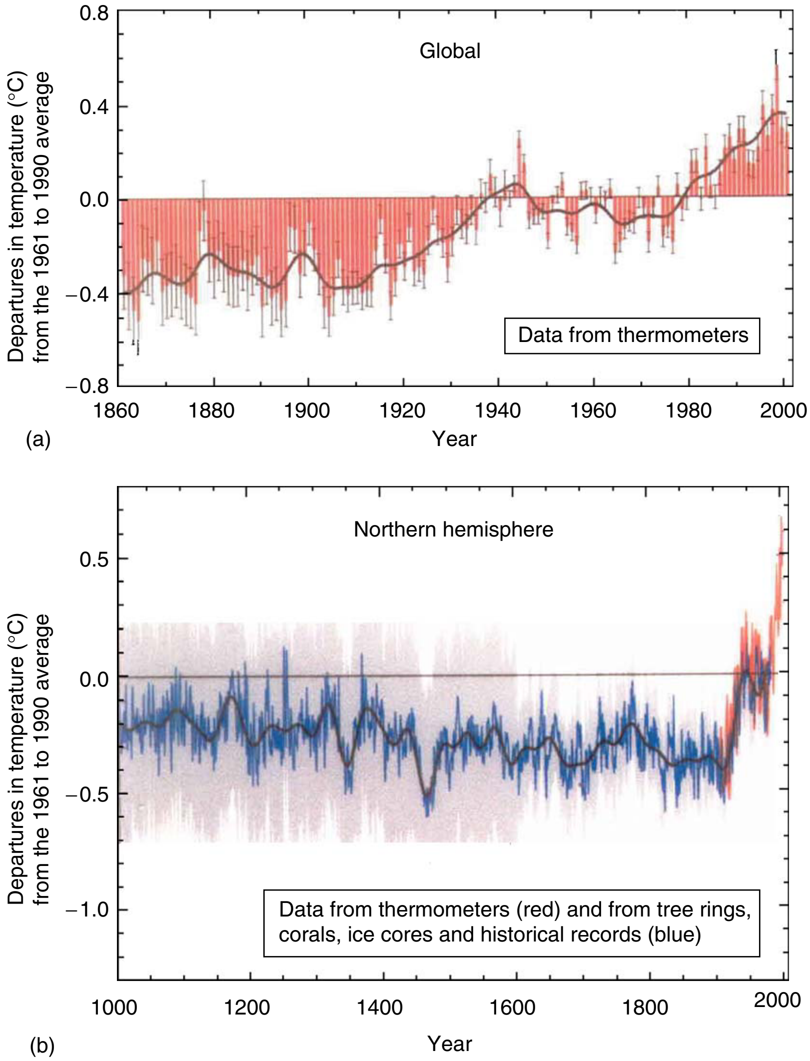

Figure 1 Variations of the earth's surface temperature over the last 140 years and the last millennium. (a) The earth's surface temperature is shown year by year (red bars) and approximately decade by decade (black line, a filtered annual curve suppressing fluctuations below near decadal timescales). There are uncertainties in the annual data represented by the thin black whisker bars (the 95% confidence range). (b) Additionally the year-by-year (blue curve) and 50-year average (black curve) variations of the average surface temperature of the northern hemisphere for the past 1000 years have been reconstructed from 'proxy' data calibrated against thermometer data (see list of the main proxy data in the diagram). The 95% confidence range in the annual data is represented by the gray region. These uncertainties increase in more distant times and are always much larger than in the instrumental record due to the use of relatively sparse proxy data. Reproduced with permission from Houghton *et al*. (2001) *Climate Change 2001*, *The Scientific Basis*. Cambridge, UK: Intergovernmental Panel on Climate Change.

increased by 1060 ppb (151%) and 46 ppb (17%), respectively, since 1750 and continue to increase. Carbon dioxide is not only a greenhouse gas, it is the raw material from which biomass is synthesized during photosynthesis. Any increase in CO_2 concentration is therefore likely to stimulate photosynthesis.

Predictions of Future Climate Change

The globally averaged surface air temperature is projected by models to increase by 1.4–5.8°C by 2100, relative to 1990 and the globally averaged sea level is projected by models to rise 0.09 to 0.88 m by 2100. Of course, prediction is dependent on the extent to which the burning of fossil fuels increases. These projections indicate that the warming would vary by region, and would be accompanied by increases and decreases in precipitation. There would probably also be changes in the frequency and intensity of some extreme climate phenomena. For example increases in the number of storms in northwest Europe are predicted, leading to the breaking or uprooting of increasing numbers of trees. These predictions assume that the current rate of emissions will not be reduced and that there will

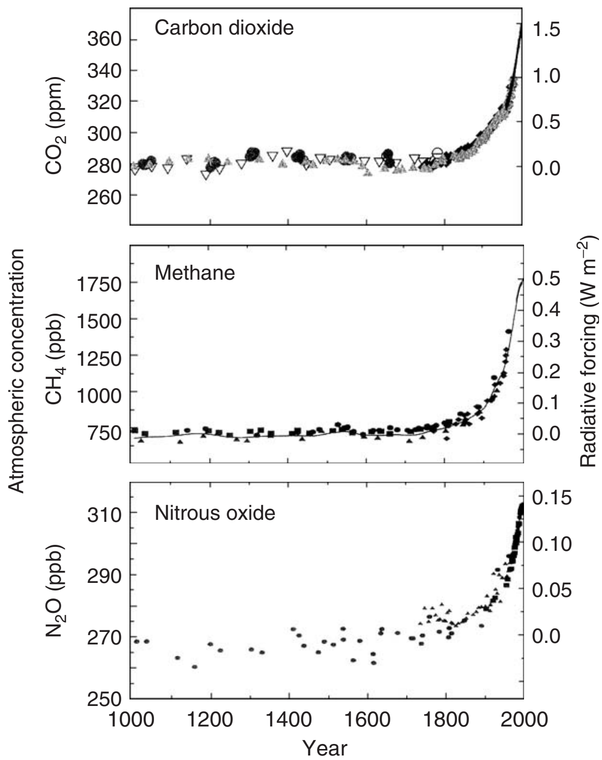

Figure 2 Indicators of the human influence on the atmosphere during the industrial era. Global atmospheric concentrations of the three main greenhouse gases (carbon dioxide, methane, and nitrous oxide) over the past 1000 years. The ice core and fern data for several sites in Antarctica and Greenland (shown by different symbols) are supplemented with the data from direct atmospheric samples over the past few decades (shown by a line for CO_2 and incorporated in the curve representing the global average of methane). The estimated positive radiative forcing of the climate system from these gases is indicated on the right-hand scale. Reproduced with permission from Houghton JT, Ding Y, Griggs DJ, *et al.* (2001) *Climate Change 2001, The Scientific Basis*. Cambridge, UK: Intergovernmental Panel on Climate Change.

be a rough doubling of current CO_2 concentrations by 2080. The exact effect on precipitation is not fully understood because of lack of knowledge about factors such as cloud formation and behaviour, but preliminary predictions have been made. It is thought that precipitation will continue to increase in the mid to high latitudes of the northern hemisphere, particularly in winter. In low latitudes there will be regional increases and decreases over the land areas. Changes in temperature, rainfall, and CO_2 concentration will naturally have profound effects on the growth, function, and distribution of forests.

Effects of Current Climate Changes on Forests

The results from modelling and other studies suggest that there are potentially beneficial impacts of climate change, such as an increase in the global timber supply from appropriately managed forests in regions of the world which are currently cold. However, this is tempered by the increased possibility of both disturbance factors, such as fires and insect outbreaks, and extreme climatic events which could lead to widespread forest decline. Recent work is now confirming these predictions. Using satellite observations it has been shown that there has been a 'greening trend' in the high northern latitudes associated with an advance of spring budburst by several days and a similar delay in autumn leaf fall. Other data from sample plots across Europe show that the growth of trees has been increasing. This is probably a worldwide phenomenon influenced by elevated CO_2 (the fertilization effect) and the deposition of active forms of nitrogen, ammonium, and nitrate (derived from farming, use of vehicles, and biomass burning). It is difficult to disentangle the effects of these three factors (temperature, CO_2, and nitrogen deposition) in natural systems but the results of many experimental studies focusing on one or both of them enable a clearer understanding of the processes underlying forest change. The experimental systems which have been used to conduct controlled experiments concerning the effects of elevated CO_2 are briefly reviewed below.

Experimental Systems Used to Investigate the Effects of Elevated CO_2 on Forest Systems

Initial studies into the direct effect of CO_2 on trees were necessarily performed on seedlings and often used seedlings rooted in pots. The environments in which the experiments were performed were often very artificial and in many cases the studies generated more questions than they answered. Their results were often qualitatively accurate, but quantitatively unreliable. Subsequent studies have used seedlings rooted in forest soil in larger open-topped transparent chambers (OTCs), and much of our understanding of how forests will respond to elevated CO_2 is from these studies.

Figure 3 shows a facility in Perthshire, central Scotland and is typical of many such OTC systems, in that it uses young trees rooted in forest soil. The chambers were set within a Sitka spruce forest and the trees were, as much as possible, treated in the same way as the surrounding forest. For example trees were planted around the outsides of the chambers to shade the trees within, in the same way as trees in the forest are shaded by their neighbors. The precipitation reaching the trees was that received through the chamber's open top and was therefore also realistic. Half of the chambers were continually flushed with ambient air, and half

Figure 3 Open top chambers (OTCs) at Glendevon, Perthshire, Scotland. Half of the chambers are flushed with ambient air and half with ambient air with additional CO_2 added to maintain a CO_2 concentration of twice ambient. The CO_2 tank can be seen in the foreground. The control room is just inside the site gates, and a nonchamber control area containing four plots with trees but no chambers can be seen at the rear, right of the photograph. This area was included to assess the affects of the chambers themselves on the trees. Photograph courtesy of the Forest Research Photo Library.

with ambient air with additional CO_2 added to maintain a CO_2 concentration of twice ambient. The airflow this generated helped to cool the chambers to more or less ambient levels, except if the ambient temperature was very warm. As the trees grew some were harvested to create space in the chambers, until only four trees per chamber were left and the trees were 4 years old. At this point the trees in elevated CO_2 had begun to grow out of the top of the chamber and the experiment could not be continued. Some OTC experiments have managed to grow trees in conditions similar to these for 6 years, but beyond this it is not practical.

More recently free-air CO_2 enrichment (FACE) systems have been developed in which air with additional CO_2 is delivered to a mature forest via a circle of pipework and vertical pipes containing CO_2-releasing jets projecting up through the forest. **Figure 4** shows FACE rings situated in a loblolly pine (*Pinus taeda*) forest in North Carolina, USA. The main advantage of such systems compared with OTCs is that they more nearly mimic the natural environment, but the main disadvantage is their huge expense both in infrastructure and in CO_2.

Effects of Increased Atmospheric CO_2 on Forest Systems

During the course of their evolution plants have responded to atmospheric CO_2 concentrations ranging from lows of 190–200 ppm during the glacial maxima to 7000 ppm 400 million years ago when plants first colonized land. Photosynthesis itself developed at a time when CO_2 was the most abundant gas in the atmosphere. The present atmospheric CO_2 concentration of around 367 ppm limits photosynthetic CO_2 fixation in almost all tree species (some herbaceous plants are not limited by the CO_2 concentration as they have an evolutionarily more advanced mode of photosynthesis). Increasing the atmospheric CO_2 concentration therefore stimulates the photosynthetic rate of trees (and most herbaceous species) and can result in increased growth rates and biomass production.

Figure 4 The free air CO_2 enrichment (FACE) rings in loblolly pine, North Carolina, USA. Three of the rings are flushed with ambient air and three with ambient air to which 200 ppm CO_2 is continually added. (The ring in the distance is a prototype.) The towers shown support white pipes with perforations for emitting CO_2 into the forest stand. Each 30 m diameter ring uses feedback control technology to control the CO_2 concentration.

Biomass It is usually found that trees in elevated CO_2 have a faster development, so they get bigger more quickly, but they are otherwise very similar to trees of the same size growing in ambient conditions. Results from FACE experiments show a 25% increase in growth in twice normal concentrations of CO_2. Similar results are found from trees growing near natural sources of CO_2 (geological sources, known as fumeroles).

Photosynthesis The reason for these increases in tree biomass in elevated levels of CO_2 is that the photosynthesis of trees is limited at current levels of CO_2. Growth is therefore almost always higher in air with an elevated concentration of CO_2. In one review of more than 500 reports, mostly from the USA, an average stimulation of 54% in elevated CO_2 was found. In long-term experiments (lasting years) plants often show less stimulation of photosynthesis than they do in short-term experiments (lasting hours), as a result of physiological adjustment.

Forest water use Plants absorb CO_2 into their leaves through tiny pores called stomata. They also lose water through the same pores which, when water is limiting is undesirable. In some experiments, elevated CO_2 causes a degree of stomatal closure and in experiments lasting several weeks or more the new leaves that have formed at elevated CO_2 often have fewer stomata per area. A reduction in the stomatal conductance could result in a reduction in the transpiration rate of the forest. Less water would therefore be removed from the soil for the same amount of carbon fixed. In the subtropics and other areas of the world where the rainfall has been decreasing this would enable photosynthesis and growth to continue for longer. A reduction in the quantity of water vapor entering the atmosphere above forests, as a result of reduced transpiration, would also affect regional and potentially global climate feedbacks. This plant atmosphere interaction can be the source of feedbacks from vegetation to atmosphere, which make the future climate very difficult to predict even though quite a lot is now known about the physiology of stomata.

Belowground processes A much-neglected area of research into the effects of elevated CO_2 on forest systems is the processes that occur below ground. These processes must be considered to fully understand forest ecosystem response to climate change. Elevated CO_2 concentrations cause a shift towards the production of more fine roots, compared with trees of a similar size growing in ambient CO_2. This is probably because trees in elevated CO_2 translocate much of their additional carbon below ground and it ends up not only as fine roots, but also as mycorrhizae (beneficial root–fungus associations), and as exudates of organic materials from the roots to the soil. The deposition of carbon directly into the soil stimulates the microbial population and it is frequently found that the respiration rate from soil beneath trees exposed to elevated CO_2 is greater than that beneath trees growing in ambient CO_2.

The quantity of litter (mainly leaves) falling to the ground from trees growing in elevated CO_2 is also increased since these trees have a larger biomass. This litter however usually has a lower concentration of nitrogen relative to carbon than litter from trees growing in ambient CO_2. The microbial soil decomposers of such litter generally require a higher nitrogen concentration and it is hypothesized that it will be degraded more slowly than litter beneath ambient grown trees, which could lead to the build up of recalcitrant carbon pools. Studies of this are inconclusive, and more research is needed. These belowground processes have feedbacks for the global carbon cycle, but mainly because of the difficulties inherent in working with this part of the ecosystem many questions still remain to be answered.

Effects of Increased Temperature on Forest Systems

The challenge facing forests during the current period of warming is the unprecedented rate at which the warming is occurring. Increased temperatures increase the rate of almost all enzymic reactions, up to the point where enzyme degradation occurs. Photosynthesis is therefore usually found to increase over relatively modest increases in temperature but soon reaches a maximum rate. Concomitant with the increase in photosynthesis is an increase in rates of cell division and expansion as well as an exponential increase in respiration, which uses up the products of photosynthesis. It is the balance between these processes of photosynthesis and respiration which determines whether increased temperature will have a positive effect on tree growth. Since respiration has been found to increase more rapidly with increasing temperature than photosynthesis, it is hypothesized that increasing temperature would have a negative impact on tree growth, but both positive and negative results have been found.

Phenology Evidence is now gathering that indicates that elevated temperature has increased the length of the growing season, particularly at high latitudes. Most of this evidence comes from a network of 'phenological gardens' which was established in 1957 across Europe, using plants that were genetically identical. Cloned specimens of trees and shrubs from a parent garden in Germany were planted at 49 sites across Europe, ranging from Ireland in the west to Macedonia in the east and Finland in the north to Portugal in the south. Dates of budburst in the spring and leaf fall in the autumn are noted annually. **Figure 5** shows the timing of leaf unfolding and leaf coloring of birch (*Betula pendula*) from 1951 to 1996 from a similar phenological

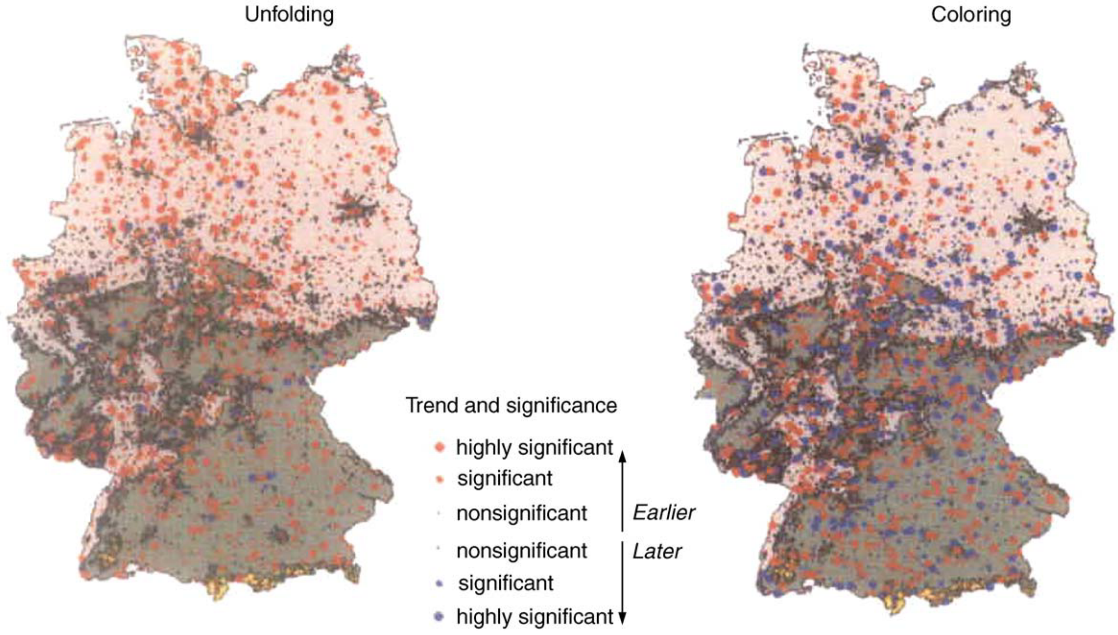

Figure 5 Linear trends in the timing of leaf unfolding (left) and autumn coloring (right) of birch (*Betula pendula*) in Germany. Data are from the phenological network of the German Weather Service and are for long observational series (20 years or more) during the period 1951 to 1996. Each point represents a series for one place. Reproduced with permission from Green RE, Harley M, Spalding M, and Zöckler C (eds) (2003) *Impacts of Climate Change on Wildlife* Cambridge, UK: WWF.

network of the German Weather Service. It shows a clear tendency for leaf unfolding to be earlier and leaf coloring to be later during this period, though the autumn shift was less than that in the spring. The Third Assessment Report of the IPCC suggests there has been a lengthening of the period during which deciduous trees bear leaves of 1.2 to 3.6 days per decade in the northern hemisphere. Moreover, spring 'greening' estimated from satellite data has advanced by 7 days since the 1960s. The regions of most greening are generally inland (except in the arctic) and are north of 50° N. In Alaska, northwestern Canada, and northern Eurasia there has been significant warming over large areas, with the greatest warming of up to 4°C occurring in the winter. This warming is associated with an approximate 10% reduction in annual snow cover from 1973 to 1992 and with an earlier disappearance of snow in the spring. However the earlier start to the growing season could increase the risk of frost damage to deciduous leaves by triggering unfurling before winter frosts have passed. Frost damage to the leaf photosynthetic apparatus would diminish photosynthetic capacity for the remainder of the season. Conifers face a similar problem timing spring dehardening and autumn hardening. There is a trade-off between fully using the extended growing season and minimizing the risk of damage by frosts.

Rapid effects at the treeline Treelines at high latitudes in the northern hemisphere shifted polewards during the early part of the twentieth century. Recent studies in the Swiss Alps show a dramatic increase in the growth of pine and spruce at the treeline. From 1820 to 2000 the temperature in the region increased by 1.02°C per century, which is much faster than the global average. The study found that the growth ring width of trees growing in the region 0–250 m below the current treeline prior to 1940 decreased with proximity to the treeline, as expected. After 1940 there was no decline in the ring width as the treeline was approached. A further study supported these finding and also found that the density of tree rings from the boreal region has decreased since 1960 – an indicator of faster growth. Despite this several studies have shown that the shift in the treeline poleward has been much less pronounced in recent decades than in the early part of the last century. It is hypothesized that increases in water stress and insect attack, amongst other factors may be possible explanations for this.

Pests and diseases Changes in climatic variables may increase frequency, intensity, and length of outbreaks of pests and diseases, especially in parts of the world which are cold. Outbreaks appear to involve range shifts northwards, poleward, or to higher elevations. For example eastern spruce budworm (*Choristoneura fumiferana*) is estimated to defoliate approximately 2.3 million ha of forest in the US and affects 51 million m^3 of timber in Canada annually. Outbreaks frequently follow droughts or dry summers, since drought and increased temperature intensify the stress on the host trees and enables the spruce budworm to lay more eggs (the number of spruce budworm eggs laid at 25°C is up to 50% greater than the number laid at 15°C). In years without late spring frosts some outbreaks have persisted and the budworm has consumed the tree's new growth. A further example is that of *Armillaria* root disease which is found throughout the world and causes significant damage on all forested continents through mortality and growth loss. In regions where the mean annual temperature is presently below the optimum (25°C) for growth of *Armillaria* a warmer climate is likely to result in increased root disease and rate of spread. In general, current forecasts of the response of forest insects and other pathogens to climate change are based on historical relationships between outbreak patterns and climate and further work to look directly at the effects of such attacks on forests which themselves are influenced by climate change is required.

Effects of Increased ENSO Frequency and Extreme Weather on Forest Systems

Many of the dry areas of the world will be particularly affected by ENSO events or other climate extremes, and forest productivity is expected to decrease. Countries in temperate and tropical Asia are likely to have increased exposure to extreme events, including forest dieback and increased fire risk, typhoons and tropical storms, floods and landslide, and severe vectorborne disease. Extreme climate events cause substantial damage to forests. For example during the 1997–8 ENSO event the drier conditions in Indonesia caused an increased frequency of forest fires resulting in a haze over the whole region lasting for many months. South America is also particularly vulnerable to ENSO and is associated with drier conditions in northern Amazonia and northern Brazil and the consequent reduction in forest biodiversity and forest productivity. In contrast southern Brazil and northwestern Peru have experienced anomalously wet conditions. Changes in precipitation levels in general are likely to lead to forest dieback and replacement of poorly adapted forest species with species more suited to the altered water availability. This will result in younger age-class distributions and altered productivity. Computer simulation modeling results have shown that ENSO events are likely to intensify under a doubled CO_2 scenario with the result that dry areas are likely to become drier and mesic areas will become wetter during ENSO events.

Computer Modeling

Computer simulation is a useful tool to address the experimental and practical limitations of research into the impacts of climate change on forest systems. For example a model called G'DAY (Generic Decomposition And Yield), developed in Australia, is an ecosystem model which integrates plant and soil processes for analysing the impact of high CO_2 on terrestrial ecosystems. The model has been used to simulate the response of nitrogen-limited forests to the expected CO_2 concentration in 2050 (about 700 ppm). It operates over periods ranging from a few years to centuries. The model predicts that there will be large initial growth increases of about 30% but that growth rates will reduce over longer timescales, as forests become limited by the shortage of nutrients. The model results change over time largely because the ratio of nitrogen to carbon in the soil changes due to the slow breakdown of organic matter.

Conclusions

Trees are sensitive indicators of climate change. There is evidence that the forests of boreal and temperate regions are responding to the current increase in temperature. They do this by unfolding their leaves earlier, shedding leaves later, and growing faster during the summer (provided there is enough water). They also respond to the increase in CO_2 concentration as enhanced CO_2 has a 'fertilization' effect on photosynthesis. In industrial and heavily agricultural regions of the world there is an additional fertilization effect because of the deposition of 'active' nitrogen (mainly ammonium and nitrate) from the atmosphere. However there are negative effects as well. As insects and pathogens complete their life cycle more rapidly at high temperatures we may expect damage by herbivorous insects and pathogens to be more acute. In the tropics, the annual growth is rarely limited by temperature but is probably very sensitive to changes in rainfall as well as CO_2 concentration. Some modeling studies suggest that Amazonian rainforest may be especially vulnerable to the effects of high temperature and drought, and decline over periods less than a century from now. Currently the temperature is increasing at an unprecedented rate, and the geographical limits of trees are likely to change. Cold regions from which trees are currently absent (at high elevation and latitude), may become colonized in the future. However, forests may die back in warmer regions.

See also: **Ecology**: Human Influences on Tropical Forest Wildlife. **Environment**: Carbon Cycle; Environmental Impacts. **Genetics and Genetic Resources**: Genetic Aspects of Air Pollution and Climate Change. **Mensuration**: Tree-Ring Analysis. **Soil Development and Properties**: Nutrient Cycling. **Tree Physiology**: A Whole Tree Perspective; Forests, Tree Physiology and Climate.

Further Reading

Houghton JT, Ding Y, Griggs DJ, *et al*. (eds) (2001) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Jarvis PG (1998) *European Forests and Global Change: The Likely Impacts of CO_2 and Temperature*. Cambridge, UK: Cambridge University Press.

McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, and White KS (eds) (2001) *Climate Change 2001: impacts, adaptation and vulnerability contribution of working group II to the third assessment report of the intergovernmental panel on climate change*. Cambridge UK: Cambridge University Press.

Saxe H, Cannell MGR, Johnsen Ø, Ryan MG, and Vourlitis G (2001) Tree and forest functioning in response to global warming. *New Phytologist* 149: 369–400.

EXPERIMENTAL METHODS AND ANALYSIS

Contents

Biometric Research
Design, Performance and Evaluation of Experiments
Statistical Methods (Mathematics and Computers)

Biometric Research

R E McRoberts, US Department of Agriculture Forest Service, St Paul, MN, USA

Published by Elsevier Ltd., 2004

Introduction

Any discussion of research in a scientific field is subject to caveats because research must of necessity be less definitive than a discussion of the field's established operational practices. First, enumerations of current research topics will be dated and subject to the perspective of the enumerator. Second, the foci of research change quickly and are subject to funding and societal priorities, perceptions of issues that demand immediate attention, and technical and technological advances. Finally, research, by definition, indicates that final solutions have not been achieved and that results may only be reported as preliminary or as works in progress. Thus, this assessment of biometric research in forest inventory should be considered a static summary in a rapidly changing discipline.

Given these caveats, current biometric research in forest inventory is focused in three major areas: forest sustainability, data delivery, and spatial estimation. With respect to forest sustainability, regional, national, and international public constituencies seek assessments of the effects on forest resources of forest management practices and environmental changes. Their demands have spawned international working groups and assessment procedures such as the Ministerial Conference on the Protection of Forests in Europe and the Montreal Process for assessing forest sustainability. Further, they have influenced national inventory programs to broaden the scope of data collection to include observation of attributes such as soil, lichens, pollutant-sensitive plant species, and down woody material. With respect to data delivery, inventory clients demand timely and precise estimates of forest attributes, summarizations, and estimates for their own areas of interest, and access to field data for their own analyses and to augment noninventory data. Finally, with respect to spatial estimation, the traditional emphasis of forest inventory has been the production of large-scale estimates of forest attributes such as area, volume, and species distribution and temporal changes in these attributes with the objective of answering the question, 'How much?' Increasingly, however, forest inventory clients are also asking the question, 'Where?' Answering the latter question requires spatial extensions of inventory plot information across the landscape. Thus, this article focuses on three biometric research topics: forest sustainability, data delivery, and spatial estimation. A vision for forest inventory that simultaneously addresses all three topics is also outlined.