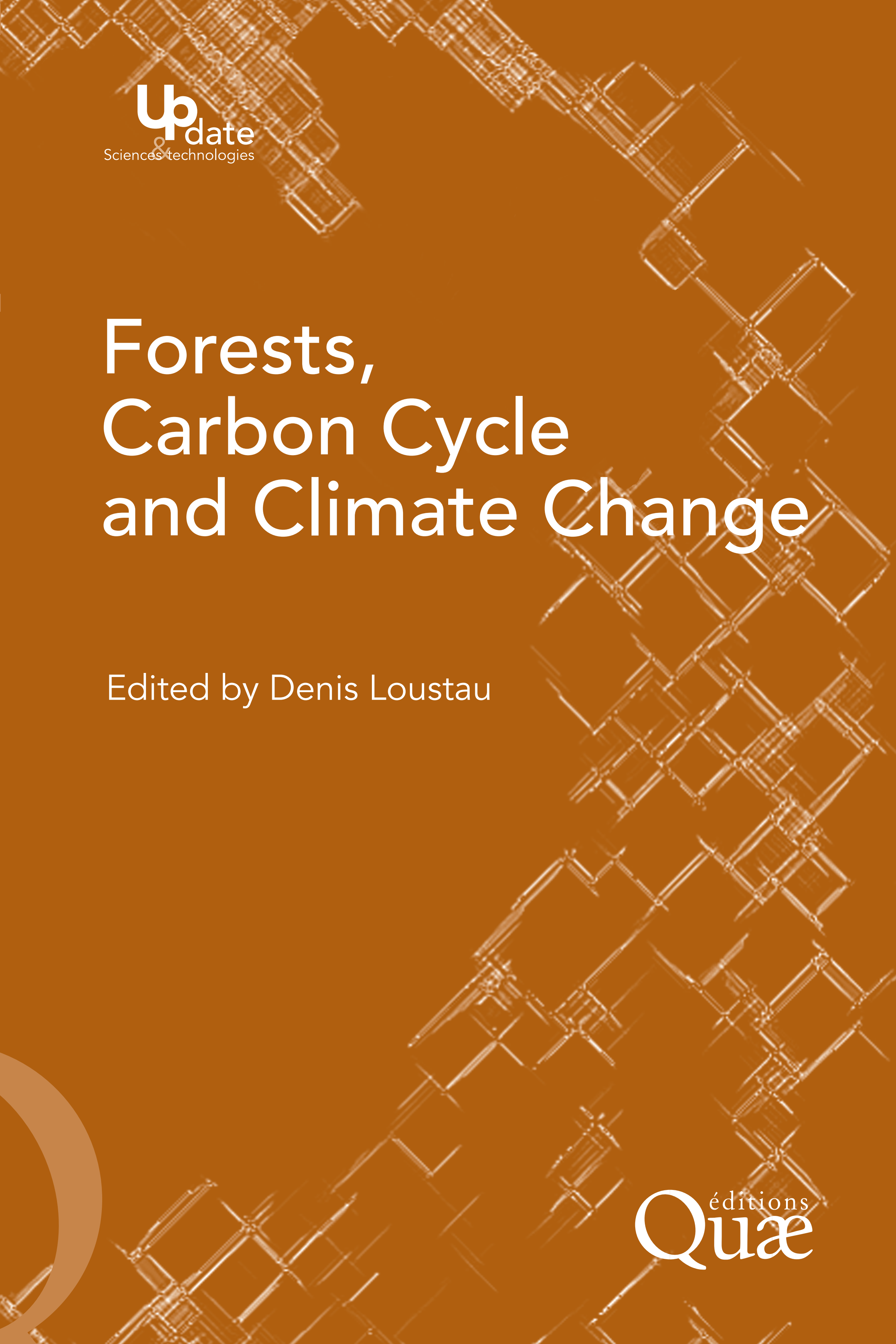

Update
Sciences & technologies

Forests, Carbon Cycle and Climate Change

Edited by Denis Loustau

éditions Quæ

Forests, Carbon Cycle and Climate Change

Edited by
Denis Loustau

Éditions Quæ
c/o Inra, RD 10, F-78026 Versailles Cedex

Collection *Update Sciences & Technologies*

La démarche qualité dans la recherche publique et l'enseignement supérieur
Claude Granier, Léandre-Yves Mas, Luc Finot, Bernard Arnoux, Nathalie Pasqualini, Vincent Dollé, coordinateurs
2009, 376 p.

Homme et animal, la question des frontières
Valérie Camos, Frank Cézilly, Pierre Guenancia et Jean-Pierre Sylvestre, coordinateurs
2009, 216 p.

Le golfe du Lion. Un observatoire de l'environnement en Méditerranée
André Monaco, Wolfgang Ludwig, Mireille Provansal, Bernard Picon, coordinateurs
2009, 344 p.

Politiques agricoles et territoires
Francis Aubert, Vincent Piveteau, Bertrand Schmitt, coordinateurs
2009, 224 p.

La mise à l'épreuve. Le transfert des connaissances scientifiques en questions
Christophe Albaladejo, Philippe Geslin, Danièle Magda, Pascal Salembier, coordinateurs
2009, 280 p.

Contaminations métalliques des agrosystèmes et écosystèmes péri-industriels
Philippe Cambier, Christian Schvartz, Folkert van Oort, coordinateurs
2009, 308 p.

Conceptual basis, formalisations and parameterization of the STICS crop model
Nadine Brisson, Marie Launay, Bruno Mary, Nicolas Beaudoin, editors
2008, 304 p.

Landscape: from knowledge to action
Martine Berlan-Darqué, Yves Luginbühl, Daniel Terrasson
2008, 312 p.

Multifractal analysis in hydrology. Application to time series
Pietro Bernardara, Michel Lang, Éric Sauquet, Daniel Schertzer, Ioulia Tchiriguyskaia
2008, 58 p.

ISBN : 978-2-7592-0385-7 ISSN : 1773-7923

Foreword

Forest carbon cycle, greenhouse effect and climate change

Forests feature commonly in fairy tales where they serve as a metaphor for wilderness and for that reason they are attractive but also a little frightening, at least for children. They also serve human needs for food and shelter, providing wood for housing and heating, berries, mushrooms and game. Forests cover a little less than 30% of the world ice-free continental area, and contain many species of trees. Tree size varies between 2 and 120 m, and trees may live from 20 to 5000 years. Such a long life makes us feel that forests are permanent features of our landscape. Yet they change with harvests, fires, pest attacks and climatic stresses. The present book deals with the carbon balance of forests, a subject that has recently become popular for several reasons. Firstly, tropical forests are disappearing at an alarming rate, although they are believed to contain over half of the living species on Earth. Secondly, forests regulate the water cycle: during drought periods, deep roots allow trees to access deep soil water and to maintain transpiration long after grasses have dried out. Thirdly, trees have a long life during which they store carbon in wood and soil. The total amount of carbon stored in tree wood is about half of that stored in the atmosphere as CO_2. Thus small variations in tree growth or in forest area have important consequences on the global carbon cycle, a major driver of climate change.

Atmospheric CO_2 has increased from about 280 ppmv in 1750 to 385 ppmv in 2008. CO_2 is a greenhouse gas: it has absorption bands in the infrared spectrum emitted by the Earth's surface, and these bands have widened with the increase in CO_2 concentration. The has resulted in an increase in the amount of infrared radiation absorbed and emitted by the atmosphere, leading to a warming of the terrestrial surface by what is called the greenhouse effect. Global warming was 0.6°C during the 20th century. It is predicted to range between 1.8°C and 4°C (with extremes from 1.1 to 6.4°C) in the 21st century, depending on emission scenarios and on climate models (IPCC, 2007). Other greenhouse gases participate in the warming but CO_2 presently accounts for over half of the total. Warming is more pronounced than average at high northern latitudes. Higher temperatures induce higher evaporation rates over the oceans and thus an acceleration of the water cycle. However, the increase in precipitation is unevenly distributed: some dry regions will become drier, while wet ones will experience more frequent flooding. Moreover, warming will lead to an increase in sea level of 0.2 to 0.6 m in 2100 (i.e. thermal expansion of seawater and decrease in continental ice), and likely much more in the following centuries threatening coastal areas.

Consequences of such a strong climate change may be favourable for northern countries such as Canada or Russia, but may be devastating for regions that either lack water (i.e. Mediterranean countries) or are submitted to flooding (i.e. Bangladesh and Indonesia). Thus a consensus has emerged suggesting that it would be wise to keep global warming below a limit of 2°C, and thus keep greenhouse gases concentration below 550 ppmv of CO_2 equivalent (Stern, 2006). Since this concentration was 455 ppmv in 2005, this objective implies a strong reduction in present world emissions by 2050 (roughly by 2, and to be fair, by 4 for the emissions of industrialized countries). This will be very difficult to fulfil considering the rapid rise in CO_2 emissions in developing countries such as China and India, and the slowness in reducing emissions in developed countries. The Kyoto Protocol asked for a modest but significant decrease in greenhouse gas emissions of industrialized countries (5.2% in average between 1990 and 2010). It was proposed in 1997, but was only ratified in 2005 (without the USA) and even this modest effort may not be achieved. Clearly stronger changes are needed, the stakes are high, and the cost of preventive measurements is significantly lower than that of repairing damage caused by climatic change after it has occurred (Stern, 2006).

Yet the increase in atmospheric CO_2 only represents less than half of the emissions from fossil fuels and deforestation, the remainder being absorbed by oceans and the terrestrial biosphere. Forests play a special role in this respect. On one hand, tropical deforestation releases about 20% of the total CO_2 emissions, on the other hand, the remaining forests seem to grow faster and thus accumulate carbon. The net effect is a global terrestrial carbon sink whose intensity is quite variable from year to year, depending on climate. This terrestrial sink is presently known only by the difference between the emissions and the atmospheric and oceanic sinks. Why is there such a terrestrial sink? How is it distributed in space and time? What is the role of forests in this sink? How does the carbon sink vary with local climate, tree species and soil type? Models of terrestrial biosphere have attempted to answer these questions, but they still require careful validation, especially for long-life species such as trees that may suffer from climatic stress several years after it has occurred.

Thus a regional study on French forests is welcome for several reasons. Firstly, France has a temperate climate with an Atlantic influence in the west and a Mediterranean one in the south; warming causes a northern movement of the Mediterranean influence, which is already discernable, making the territory a sensible location. Secondly, forest inventory is well developed in France with over 100,000 plots sampled every decade, and this has been used to study species distribution of forest trees, carbon stocks and variations. Thirdly, there are several intensive flux measurement sites for both deciduous and coniferous species, some being operational for over a decade. Most sites also support process studies on trees and soil, suitable for model parameterization.

What do we want to know about the carbon cycle of temperate forests? We wish: (i) to quantify their role as a carbon sink; (ii) to understand the factors acting on this sink; and (iii) to incorporate our knowledge into models predicting the evolution of this sink in the coming decades. We also wish to know the impact of climate change on wood production for the main forest trees in order to adapt forest management to these changes. Global warming is likely to increase the frequency of climatic stresses such as heat waves or long dry periods. What will be the effect of such stresses on trees in terms of forest fires or pest attacks? These questions are addressed here.

The present book is organized into three parts: the first one presents the actual forest carbon cycle in temperate and Mediterranean climates, including the dynamics of soil carbon and the total carbon stock of French forests based on forest inventories. The second part uses models to simulate the effects of climate change on tree phenology and forest carbon balance. The third part deals with the impact of climate change on forest vulnerability: change in geographical distribution of forest tree species and pathogenic fungi, and the consequences on forest fires and pest attacks.

Professor Bernard Saugier
Member of Académie d'Agriculture de France

References

IPCC, 2007. Summary for Policymakers. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller, eds). Cambridge University Press, Cambridge. [http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf]

Stern N., 2006. *The Economics of Climate Change: The Stern Review*. [http://www.hm-treasury.gov.uk/stern_review_report.htm]

Acknowledgements

The results presented in this book originate from the project CARBOFOR (2002–05) funded by the French Ministère de l'Écologie et du Développement Durable (MEDD) and Ministère de l'Agriculture et de la Pêche (MAP) within the framework of the governmental programme called "Management and Impacts of Climate Change" (GICC). The project involved 14 participants belonging to INRA, CNRS, IFN, CEA, CIRAD, CNRM/Météo-France and the Universities of Paris-XI-Orsay and Orléans. We are grateful to M.M. Maurice Muller (MEDD, GICC), Claude Millier (Agro ParisTech, GICC), Guy Landmann (MAP, GIP Ecofor) and Professor Bernard Saugier (University of Paris XI - Orsay) who supervised the implementation of the project. The authors would like to thank all partners and collaborators who contributed to the implementation and performance of this research work. I am pleased to acknowledge Professor G.M.J. Mohren (University of Wageningen) and Professor J. Grace (University of Edinburgh) who coordinated the pioneer FERN, LTEEF-1 and LTEEF-2 European projects from which this research was inspired.

Beyond the project CARBOFOR itself, the edition and publication of its results constituted an additional challenge that could not be met without the support of many organizations and people: the Ministry of Ecology, ECOFOR (Jean-Luc Peyron and Guy Landmann) and INRA (mission MICCES, Bernard Seguin) who maintained an interest in the project and provided funds for this publication. Marie-Pierre Reviron, Anne-Marie Bouchon, Stéphanie Hayes and QUAE editors, Anne-Lise Prodel, Valerie Howe and graphic assistant, Joëlle Delbrayère played an important role in the shaping of this book. All authors, reviewers and assistant editors must also be thanked for the efforts they have made to write this book in English and present their results as clearly as possible.

Denis Loustau

Contents

Part I
The carbon cycle in temperate and Mediterranean forests

Part II
Forest under a changing climate

Part III
Climate change and forest vulnerability

Executive summary

The French metropolitan area occupies a unique ecological place in Europe in the context of climate change being at the confluence of four climate zones – oceanic, continental, Mediterranean and mountain. Around 28% is covered by forests managed by public and private landowners. French forests offer, therefore, a great diversity of silvicultural types. The French metropolitan area includes the northern, southern or altitudinal margins of a large number of tree and pathogen species. This range makes it challenging to observe, analyse and simulate the effects of climate change on forests at regional and sub-regional scales. The aims of the CARBOFOR project were thus:

- to assess the present status of French forest ecosystems from the point of view of the carbon cycle (Part I);
- to describe the potential effects of climate change on its phenology, productivity and carbon cycle at a range of spatial scales (Part II);
- to provide some insights into the possible future of tree species biogeography, pathogens and fire risks (Part III).

An important characteristic of climate change is its spatial variability. Recent modelling studies at the sub-regional level show that changes in precipitation and temperature regimes vary at the sub-regional scale, for example, between the south and north of Europe. Since the geographical limits for many tree species are shaped by climate constraints such as temperature and drought, a change in climate can have a dramatic and asymmetric effect at the margins of natural areas, removing low temperature limitations towards the poles whilst increasing water deficits and high temperatures at lower latitudinal limits.

Climate change can potentially affect tree species directly as well as indirectly through local site characteristics that control the availability of resources. Assessing these effects on tree and stand functioning, therefore, requires a quantitative description of changes in the variables of interest at the local level. In this report, we summarized the results of predictions based on 50 × 50 km grid climate scenarios, we analysed the interactive effects between management scenarios and site fertility on forest growth and carbon balance, potential habitat areas for tree species, areas at increasing risk of pathogen infection and fires and its potential impacts on flora in the Mediterranean zone.

Present status of the forest carbon cycle and productivity

The comparative analysis of carbon flux and carbon balance of forest sites led to the conclusion that the main source of variability in the carbon cycle of French and tropical forests is their physical structure. Differences in carbon, water and energy exchanges attributed to variations in tree age and species composition are mainly driven by variations in leaf area index, canopy height and relative importance of the canopy layers (Chapter 2). Accordingly, the carbon dynamics in humus organic layers exhibit a strong temporal pattern during the ecosystem life cycle, building up the OH and OF layers within a period of 30 to 50 years in *Fagus* and *Pinus* forest of the western part of France (Chapter 3).

Several options used for estimating the amount of carbon stored in forest tree biomass are reviewed and illustrated (Chapter 4). The estimate of the total amount of carbon in French metropolitan forest and its temporal dynamics are presented in Chapter 5. Interestingly, this analysis confirms the increase of carbon stock in managed temperate forests and shows how errors and uncertainties in parameter estimates propagate in the calculation of carbon stock value.

Climate scenario

The French national meteorological office Météo-France atmospheric model ARPEGE/Climate (3.0) has been used to simulate present climate and 21st century climate through a 140-year numerical experiment (Chapter 6). The greenhouse gas and aerosol concentrations were prescribed by the so-called IPCC B2 scenario. Ocean surface temperatures are provided by a model with a coarser resolution coupled to an oceanic water circulation scheme. The radiative forcing scheme includes four greenhouse gases (CO_2, CH_4, N_2O and CFC) in addition to water vapour and ozone, and five aerosol classes – land, marine, urban, desert and sulphate, respectively. The model predicts an increase in temperature reaching +4°C in summer over south-western Europe and a shift in seasonal precipitation from summer to winter by 50 mm together with significant sub-regional variations.

Phenology

The phenology of vegetation is a major component of forest ecosystem productivity and influences the annual balance of energy and gas exchange by forest ecosystems. A review of the variability of leaf unfolding dates in major forest trees shows that on average leaf unfolding has been advancing at a mean rate of 2.9 days per decade since 1950 in tree species from the temperate zone with some species variation (Chapter 7). Although current patterns can be estimated from satellites, we still lack the ability to predict accurately and widely future trends in the response of phenology to climate change because leaf phenology and its intra- and inter-population variability are difficult to parameterize. The observed changes in tree phenophases during the last decades across the French ICP forest network show that leaf unfolding, growing season duration and leaf colouring have shifted in the last few decades to earlier dates than those previously observed (Chapter 8).

If changes in phenology remain linear with warming, using present trends we can estimate that leaf unfolding should advance on average at a rate of 5.4 to 10.8 days per decade over the period 2000–50. Thus, by 2050, leaf unfolding of forest trees could occur on average 27 to 54 days earlier than at present. Such a change should have major consequences on forest productivity and on the specific species composition of forests over a given area. A few species, with chilling requirements, would be delayed by a warming climate. However, the dual action of temperature on phenology (i.e. the action of cool temperature to break dormancy followed by the action of warmer temperatures promoting cell growth during quiescence) should lead to a non-linear response of phenological change to warming.

Forest growth and biogeochemical cycles

Biophysical models such as CASTANEA, GRAECO and the large-scale ORCHIDEE model were used to simulate the annual carbon and water balances and wood production of forests averaged over complete forest rotations. These models were first evaluated against data collected across a network of flux sites of the CARBOEUROPE project (Chapter 9) and then used in predictive mode with a climate scenario based upon the IPCC B2 economic scenario of CO_2 accumulation in the atmosphere (Chapter 10). A range of management scenarios and site conditions were considered.

The models predict a slight increase in potential forest production until 2030–50 followed by a plateau or a declining phase in 2070–2100 sensitive to geographical variation, with the northern part of the temperate zone being more favourable for wood production than the southern temperate and Mediterranean zones. In the southern temperate and Mediterranean forests where the largest increase in the growing season water deficit occurs, the CO_2 enhancement of gross primary production was overshadowed by drought impacts. The changes in forest production, as predicted for different forest management options and site conditions, are explained by the counterbalancing effects of rising CO_2, water deficit and the fact that ecosystem sensitivity to climate decreases with age. This interaction between climate, CO_2, nitrogen and water availability and management regime is an important outcome of the modelling analysis.

In terms of the geographical variation of climate change impacts, our analysis refines the conclusions published on the global impacts of climate change on European forests so far and confirms the hypothesis for a strong regional pattern in the 1990–2050 predictions for age-independent net ecosystem productivity, with larger increases in net ecosystem productivity for the boreal zone and a decline across Mediterranean forests.

Biogeography, pathogens and risks

Using botanical inventory data collected by the National Forest Inventory, empirical models relating the frequency of a given species to climate parameters such as minimum and maximum temperature, monthly precipitation and Penman's potential evapotranspiration were established and used for predicting the change in potential habitat areas under the climate scenario considered (Chapter 11). This approach predicts a dramatic change in the geographical distribution of potential areas for tree species with an extension of the southern temperate and Mediterranean species by 150 to 250 km northwards by 2100, together with a similar recession of most oak species, silver fir and beech at their southern edges. These predictions are consistent with observations of the decline of some beech and Scots pine forests at their southern margins, for example, in the plains of southern France and the southern Alps.

Several types of models were used to simulate the effect of the climate change scenario on pathogens and diseases: statistical biogeographical models based on distribution data from specific surveys, a specific epidemiological model and the generic model CLIMEX (Chapter 12). Unsurprisingly, poleward extension of thermophilic pathogen and insect species and associated damage risk is predicted. However, the effect of warming would be counterbalanced by the negative effect of decreased summer rainfall for some species. Due to the high dispersal potential of many fungi, the colonization of new regions becoming climatically favourable could put them into contact with naive host populations (i.e. with no co-evolution or co-adaptation history), with the same potentially dramatic consequences as those observed with introduced parasites.

In Mediterranean and southern temperate forests, the duration of the annual period when fire risk is high will be extended by climate change. Together with ongoing land abandonment and the increase in urban areas and peri-urban forest areas, where ignition frequency is highest, the risk of fire in southern, mostly unmanaged, forest ecosystems will increase as already observed since the 1970s. Under a changing climate, the fire return interval might decrease from 72 to 62 years for Mediterranean forests and from 20 to 16 years for shrublands. In turn, fire frequency curbs the extension of forests into southern Europe as increased fire frequencies leads to a domination of fast growing shrubs or resprouting species (Chapter 13).

Lessons for managing forest in an uncertain future

Where climate change effects are beneficial to forest functions, in northern temperate, continental and boreal forests, our results suggest that optimizing forest management should aim at reducing the effects of limiting factors, for instance, through fertilization. Conversely, where detrimental effects of future climate are expected through increased water deficit, for example, in southern temperate and Mediterranean forests, enhancing the ecosystems resistance to drought and fire using species substitution, understorey control, site preparation and reductions in the maximal value of leaf area index could be appropriate strategies to adopt.

For future research, the complex interaction between climate and atmospheric composition calls for: (i) an assessment of the entire environment rather than single factor response; and (ii) regional studies to account for local features of the forest environment and management. The forest function must also be considered.

Since climate change is provoking a continuous, but not monotonous, change in site productivity, the management of a given forest must be revised dynamically along its life course. At the southern margin of geographical areas, management aiming at an optimal adaptation of forests should be considered, favouring, for example, multi-age and mixed forest stands including pre-existing species and their southern variants and maximizing intra-specific diversity.

Disease management in forest ecosystems has to rely on an anticipatory and preventive approach based on risk analysis. Since simulated geographical ranges are only potential envelopes in which parasites may establish, depending on their dispersal ability, the application of strict hygiene measures, based on the most probable dissemination pathways of organisms (in seeds, wood and plants) is necessary in order to delay the establishment of parasites in climatically favourable zones.

Part I

The carbon cycle in temperate and Mediterranean forests