Chapter 6
Forests, Carbon Pool, and Timber Production

Robert Jandl, Silvio Schüler, Andreas Schindlbacher, and Christian Tomiczek

Contents

R. Jandl (✉) • A. Schindlbacher
Department of Forest Ecology, Robert Jandl Forest Research Center (BFW),
Seckendorff Gudent Weg 8, 1131 Vienna, Austria
e-mail: robert.jandl@bfw.gv.at; andreas.schindlbacher@bfw.gv.at

S. Schüler
Department of Genetics, Silvio Schüler Forest Research Center (BFW),
Hauptstrasse 7, 1140 Vienna, Austria
e-mail: silvio.schueler@bfw.gv.at

C. Tomiczek
Department of Forest Protection, Christian Tomiczek Forest Research Center (BFW),
Seckendorff Gudent Weg 8, 1131 Vienna, Austria
e-mail: christian.tomiczek@bfw.gv.at

R. Lal et al. (eds.), *Ecosystem Services and Carbon Sequestration in the Biosphere*,
DOI 10.1007/978-94-007-6455-2_6,

Abstract Forests play an important role in the mitigation of climate change, and store substantial amounts of carbon (C). The living biomass contains 363 Pg C and the soils an additional 426 Pg C. Given that forests annually exchange about sevenfold more carbon dioxide (CO_2) with the atmosphere by photosynthesis and respiration than is emitted by burning of fossil fuels (currently 9.1 Pg C), the role of forests in the global C cycle is significant. Land-use change contributes 10 % or 1.1 Pg C to the annual CO_2-emissions and leads to significant changes in the C pool. Presently, the temperate forests are a C sink because the forest area increases annually by between 0 and 0.5 %, and the productivity of forests is increasing. Deforestation in the tropical zone is a source of CO_2. Ecosystem disturbances such as storm damages and insect infestations are causing economic loss, and destruction of forests leads to the loss of numerous ecosystem services. Disturbances are partially a component of natural ecosystem dynamics, partially they are triggered by climate-change effects, and partly by changes in forest management. The different effects are often difficult to disentangle. Foresters respond to climate change by developing strategies of adaptative forest management. The opinion on successful concepts is still unconsolidated, both due to differences in the anticipation of the extent of climate change, and due to different opinions on the resilience of different forest types. Simulation models and manipulative experiments are important tools for the development of strategies of adaptive forest management. With respect to the role of forests in the global C cycle two opposing opinions exist. Firstly, it is possible to focus on C sequestration in standing forests, alternatively, forest biomass can be intensively used in order to provide timber for the substitution of other materials, and forest biomass for energy. From a forester's perspective the active management of forests offers more opportunities than management towards old-growth forests with maximized C stocks in the standing biomass. Intensive forest management needs to follows the principles of sustainability. This paradigm is instrumental in forest politics. The use of criteria and indicators help to approximate and maintain a desired status of forest ecosystems.

Keywords Carbon • Forest ecosystem • Land use • Disturbance • Ecosystem services • Adaptive forest management • Sustainable forestry

6.1 Carbon in Forests

Forests play a major role in the terrestrial C cycle and in our efforts to manage the amount of C in the atmosphere. Forestry is, therefore, an important element of a voluntary C market and of government efforts of mitigating climate change. Presently, global forests are major terrestrial C sinks, whereas grasslands, crop lands, and many peatlands are C neutral or even a net source of CO_2. Accordingly, C sequestration in forest is an ecosystem service receiving considerable attention. Inventory data from around the world show the distribution of C sources and sinks, the importance of temperate and boreal forests as current sinks and the enormous

Table 6.1 Forest area, estimated total carbon pools in the forest biomass, soil carbon pool in forest soils to a depth of 1 m and carbon density for different climatic zones (Pan et al. 2011)

Climatic zone	Area (10^6 ha)	Living biomass (Pg C)	Dead biomass (Pg C)	Soil (Pg C)	Total (Pg C)	Carbon density (MgC ha^{-1})
Boreal	1,135	54	16	193	272	239
Temperate	767	47	3	69	119	155
Tropical	1,949	262	546	155	471	242
Total	3,851	363	73	426	861	224

1 Pg = 10^{15} g

fluxes (sources and sinks) contributed by tropical forests. Currently, forests absorb about 27 % of the annual CO_2 emissions from fossil fuels and are providing an arboreal discount on CO_2 emissions (Le Quéré et al. 2009). The absorption of CO_2 comes on top of a number of other ecosystem services that are provided by forests (Shvidenko et al. 2007). Factoring in the oceans and other terrestrial ecosystems the total absorption increases to over 50 %. Without these natural sinks, as result of increasing anthropogenic CO_2 emissions, the rate of CO_2 increase in the atmosphere would be substantially higher (Pan et al. 2011). Nevertheless, the terrestrial ecosystems encompass only one of several big sinks of CO_2. In the past 50 years, the fraction of CO_2 emissions remaining in the atmosphere has likely increased, presumably due to a declining sink strength of the oceans (Le Quéré et al. 2009).

6.1.1 Pools and Fluxes of Carbon

Organic C in forests is stored in the biomass of living and dead trees, in the forest floor and in the mineral soil. Forests are the only vegetation type where the biomass is a similar sized C pool as compared to the soil. By far the largest C pool is found in tropical forests where the deforestation dynamics are most dominant and where the available database on C stocks is partly sketchy (Dixon et al. 1994; Bonan 2008). In boreal and temperate forests the soils may store more C than the tree biomass, whereas tropical soils may contain about half as much C as the tree biomass. The total C pool in forests exceeds the amount of C in the atmosphere (Denman et al. 2007). Temperate forests that are thoroughly investigated store less than 15 % of the global C pool in forests. Due to the intense management the relative amount of deadwood is by far smaller than in other climatic zones (Table 6.1).

Many countries have access to long-term forest inventory data enabling to establish solid estimates of the C pool in the tree biomass (Lindner and Karjalainen 2007; Nabuurs et al. 2010; Tomppo et al. 2010). Their main purpose is traditionally the estimation of the harvestable stem volume. With biomass expansion factors and functions an estimation of the C pool in the tree biomass is possible (Zianis et al. 2005; Enquist and Niklas 2002). Substantial data gaps exist in tropical areas and in extensively managed boreal forests. For these regions, remote sensing approaches are the method of choice.

The soil organic carbon (SOC) pool contributes about 50 % to the total forest C pool, and exceeds in boreal and temperate forests even the C pools in the biomass. Forest soil inventory data are less abundant than information on the aboveground forest biomass. The data on temperate forest ecosystems in Table 6.1 are well supported (Food and Agricultural Organization of the United Nations 2006; Tomppo et al. 2010; Smith et al. 2009). Data gaps in the C pool in wetland soils and frozen soils prevail. Soil organic matter (SOM) is extremely heterogeneous with respect to its chemical properties, its decomposability, and consequently its age. Moreover, the small scale variability in the field is large. SOM forms from residues of plants, soil microorganisms, and soil fauna. The litter from roots is as relevant as the C input from needles and leaves. The assessment of the SOC pool may be derived from the total content of organic C, soil bulk density, rock content and soil depth as parameters, where soil bulk density is often estimated with pedotransfer functions (Rodeghiero et al. 2009; Schmidt et al. 2011). Remote sensing techniques are so far not useful for the assessment of SOC pools.

The major C fluxes are the fixation of C in the biomass by photosynthesis, the release of CO_2 by autotrophic and heterotrophic respiration, and harvesting. Photosynthesis and respiration depend on the productivity of the forest and hence ultimatively on the climate. The turnover of C in the living biomass is fast and highly sensitive to ecosystem disturbances. The biomass pool can expand only slowly by an increased growth rate and a lower frequency or severity of disturbances, but can be degraded quickly (Körner 2003). The net C fluxes within a particular period can be directly measured, e.g., by the eddy covariance method, or assessed from repeated inventories, or estimated by modeling approaches (Baldocchi 2003; Luyssaert et al. 2010). A large quantity of SOC is allocated to an arbitrarily defined inert pool. In the modeling exercises the soils are mostly represented by pools of different turnover rates. This approach is transparent but does not reflect the current understanding of SOC dynamics (Friedlingstein et al. 2006; Schmidt et al. 2011). While the eddy covariance technique provides the CO_2 budget of the entire ecosystem, the elements of the C fluxes need to be measured separately, such as C fixation via photosynthesis, litterfall, and soil respiration.

The quantification of C pool changes from repeated inventories is accurate for the aboveground biomass, because the relevant tree parameters such as stem diameter and height are directly measured. The estimation of the belowground biomass is less certain because it is often based on biomass expansion factors and functions that are supported by much fewer measurements. The assessment of a regional SOC pool is also uncertain because in most regions very few forest soil inventories are conducted. In undisturbed forest ecosystems, the decadal SOC pool changes are small and difficult to detect against the background of the large SOC pool. This challenge offers ample room for the application of SOC simulation models. The mechanistic understanding of the persistence of SOC is incomplete. The stability of the SOC pool depends not only on intrinsic soil properties, but is greatly controlled by the surrounding soil biological ecosystem. However, a precise assessment of

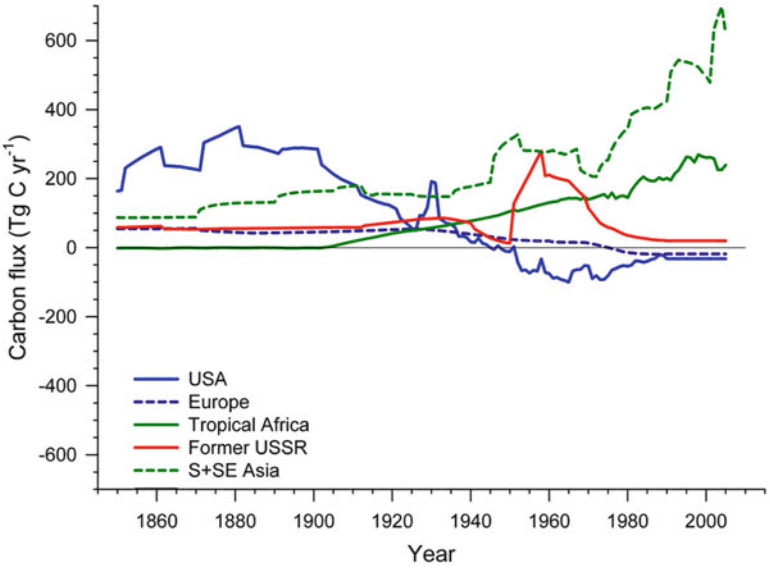

Fig. 6.1 Annual net flux of C to the atmosphere from land-use change for several regions (Data from Houghton 2008)

C pool changes is indispensable in the context of the monitoring and verification of the performance of C sequestration projects, and for the reporting of national greenhouse-gas (GHG) inventories.

6.1.2 Land-Use Change Effects

The size of the C pool in an ecosystem may be increased by improved land management and by the change in land use. By far larger than any modification of the land management is the effect of land use changes, and 30 % of the land surface has undergone anthropogenic land-use change (Houghton 2008; Schils et al. 2008). The replacement of forests by agricultural crops reduces the C pool in the biomass instantaneously, and leads to a decline in the SOC pool in the long run (Don et al. 2011). Deforestation and an exploitative use of natural resources is a known phenomenon of economies in transition. In Fig. 6.1, the C fluxes due to land-use change between 1850 and 2005 are shown. Europe had many periods of intense deforestation, starting already as soon as 1,000 years BC. The pattern of reforestation and forest loss reflects the demand for cultivatable land, political turmoils, and the effects of the bubonic plague. The reforestation/deforestation history in the Americas is clearly linked to the collapse of the indigenous populations and the arrival of Europeans (Pongratz et al. 2011). As a general pattern, it is proposed that deforestation rates are high in the initial phase of the development of a society, but decline as the knowledge in agriculture is enhanced and crop production is increasingly performed on soils with high productivity. In Europe, the temporal development of land cover and population density was uncoupled during the last century (Kaplan et al. 2009; Mather and Needle 1998; Reick et al. 2010).

The deforestation in the tropical zone is slowing and is currently about 1 Pg C year^{-1} or 10 % of the total CO_2 emissions (Friedlingstein et al. 2010). The downward trend of CO_2-emissions due to land-use change is partly a consequence of legal actions against deforestation in many regions (Tollefson 2012). Due to the implementation of improved soil management methods the C release is expected to be smaller than in the past. Nevertheless, soils will continue to lose C due to climate and land-cover changes (Eglin et al. 2010). With afforestation programmes the trend can be reversed. In the current offset of GHG emissions, temperate forests have a prominent role. The capacity of C sequestration due to afforestation is, however, limited. Replenishing the C pool is in some instances a one-time event such as the recovery of European temperate and boreal forests after intensive forms of land use, particularly in mountain areas and on marginal agricultural land. In addition, large tracts of Eastern European and Russian agricultural land were abandoned and have since reverted to forest (Vuichard et al. 2008). In China, million ha of afforestation land that had been used for other purposes or was barren, has now been turned back into forest (Food and Agricultural Organization of the United Nations 2006; Führer 2000; Seppälä et al. 2009; Wang et al. 2007). It will be difficult to find open land for afforestation in the future for maintaining the current sink, especially when considering an increasing demand for agricultural land for the production of food, feed, fibre, and fuel.

The major effect of C sequestration in afforestation programmes is mainly the quick accumulation of aboveground biomass. In the soil, the main effect is the formation of an organic soil layer, predominantly under coniferous forests. The accumulation of organic material has a duration of few decades and depends on the history of site management and on physico-chemical soil properties. The effect of land use change from agricultural land towards forests on the C stock in the mineral soil is small and simulation models tend to show a quicker response than indicated by field observations (Karhu et al. 2011; Laganière et al. 2010; Vesterdal et al. 2011).

When managing land with the objective of maximizing C sequestration there are several points for scrutinization. Afforestation/reforestation projects can decrease the biodiversity. An example is the gradual encroachment of forests into high-elevation pasture land in mountain regions of the temperate zone (Thuiller et al. 2005). The newly establishing forest ecosystems harbor less herbaceous species than the previous grassland ecosystems. In addition, the greater homogeneity of the landscape can reduce the scenic beauty. This argument is relevant in touristic areas. In regions with an intermediate snow cover such as the temperate and the boreal zones and many mountain ranges the effect C sequestration effect may be partially offset by the change in the surface albedo. A snow cover effectively reflects incoming radiation whereas the darker canopy of a forest plantation would absorb it. The climate forcing by albedo cooling dominates warming as a result of CO_2 emissions, particularly in the boreal region (Anderson et al. 2010). A forest cover would, therefore, have

Fig. 6.2 The dark surface of the forest canopy may absorb more radiation than the effectively reflecting snow cover on agricultural land and range land (*Picture*: *Robert Jandl*)

a warming effect despite the enhanced fixation of atmospheric CO_2 in biomass and soil (Fig. 6.2). An alternative concept to the maximization of the C pool in the living tree biomass is sustainable forest management because it ensures a continuous flow of wood products and bioenergy while maintaining or increasing the C stock in the ecosystem.

6.2 Climate Change

Climate change manifests itself in different ways. Most obvious is the increase in the global mean air temperature. More difficult to verify is the change in the precipitation regime, and the changing frequency of drought events. In addition, forests are responding to the fertilizing effect of the increasing partial pressure of CO_2 (Calfapietra et al. 2010). The currently observed warming trend is by far higher than during the paleocene-eocene warm period, and modern atmospheric CO_2-concentrations probably not occurred in the last 800,000 years (Kump 2011; Lüthi et al. 2008). Forests are an important element of climate-change mitigation efforts due to their ability to sequester C, especially when new areas are afforested or reforested, and due to the production of biomass for renewable energy replacing fossil fuels. Considering how well trees cope with seasonal changes and interannual variations of weather conditions it can be assumed that forests are able to adapt to slow changes in the site climate. However, rare extreme events have a strong effect on the development of ecosystems. The character and severity of impacts from extreme events depend on the extremes themselves, and on the exposure and vulnerability of the forests. Globally, a high probability of an overall decrease in the number of cold days and nights, and an increase in the number of warm days and nights has been predicted (IPCC 2012; Rahmstorf and Coumou 2011). There have been significant trends in the number of heavy precipitation events in some regions. While it is not currently possible to reliably project specific changes at the catchment scale, there is high confidence that changes in climate have the potential to seriously affect water management systems. However, climate change is in many instances only one of the drivers of future changes, and may be not necessarily the most important driver at the local scale (IPCC 2011).

The emissions of GHGs are still rising and so far it has not even been possible to reverse the trend. From 2000 to 2009, the C in the atmosphere rose annually on average by 4.1 Mg, and in 2010 the global C emissions increased by an unprecedented high rate of 5.9 %. The rate of increase in CO_2 concentrations in the atmosphere has never before occurred on earth (Kump 2011). For mitigation of climate change, forests will play an important role although it is well understood that the mitigation potential of forests is not the ultimate solution. A modeling exercise has clearly shown that the efficiency of terrestrial ecosystems to absorb the anthropogenic C perturbation will decline in a future climate. A larger fraction of anthropogenic CO_2 will stay airborne if climate change is accounted for. Should climate change advance too far and terrestrial ecosystems transform from C sinks to sources, and begin releasing vast quantities of C into the atmosphere, human efforts to mitigate climate change may be overwhelmed. Drastic emission reductions are required to limit global warming to the 2°C in order to reduce climate change risks, impacts, and damages (Friedlingstein et al. 2006; Meinshausen et al. 2009; Peters et al. 2011; Smith et al. 2012).

6.2.1 Forests in a Warmer World

Forests have proven to be able to adapt to changes in environmental conditions very well in the past. Only therefore have they been able to inhabit about 30 % of the global land areas (Food and Agricultural Organization of the United Nations 2006). Climate change may exceed the adaptive power of forests. There may be two vastly different possible responses of forests to climate change. An optimistic scenario indicates that in a warmer world, trees will grow faster, prosper in a longer growing season, flourish in areas where they had never before grown, take up more C and increase the C sink. A pessimistic scenario is that warmer temperatures will cause more forest fires, more insect infestation, more dead and dying trees, more peatland decomposition, thawing of permafrost and the transformation of forests into C sources. Both avenues of argumentation are possible based on experimental evidence. Thus, the effects of climate change on forests C storage may strongly depend on the geographical location of the forest (Lindner et al. 2010).

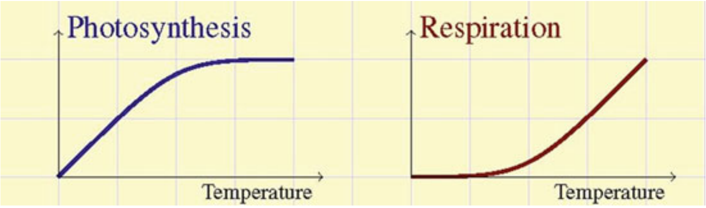

Fig. 6.3 Idealized responses of plant photosynthesis and soil microbial respiration to increasing temperature

Processes in forest ecosystems do not respond equally to warming. Figure 6.3 schematically shows that the warming effect on the productivity of trees tends to saturate with increasing temperatures whereas the heterotrophic respiration of soil microorganisms accelerates. Such textbook knowledge often fails to describe ecosystem dynamics. Under field conditions the temperature dependence can be modified by effects like drought and ecosystem disturbances, and by internal factors such as soil properties. However, generally a quicker turnover of C in terrestrial ecosystems is projected (Friedlingstein et al. 2006).

The heat wave in parts of Europe in the summer of 2003 has offered the opportunity to quantify the response of different tree species to hot and dry conditions (Ciais et al. 2005). In Germany, the productivity of Norway spruce (*Picea abies* (L.) Karst.) declined and did not return to previous levels in several years, partially because the summer of 2006 was also hot and dry. The growth decline of Scots pine (*Pinus sylvestris* L.) was by far smaller and mostly confined to 2003. The growth pattern of pine reflects the condition during the growing season and shows a quick recovery when the climate conditions return to average levels. European beech (*Fagus sylvatica* L.) did respond in the year after the summer drought with a strong growth decline and recovery phase of more than 3 years. In contrast, oaks (*Quercus sp*. L.) did not respond at all. These thermophilic species are obviously not affected by hot summers (Beck 2010). In a modeling exercise, the heat wave of 2003 led to reduction of the gross primary productivity over Europe of 30 %, and turned the terrestrial ecosystems into a temporary C source, reversing the effect of 4 years of C sequestration (Ciais et al. 2005).

6.2.2 Climate Manipulation Experiments

Simulation models play a dominant role in the prediction of the response of forests to climate change (Heimann and Reichstein 2008; Kurz et al. 2009; Luyssaert et al. 2010). There is broad consensus that a mere modeling approach is insufficient because models incorporate the state-of-knowledge and are built based on data of past experiences. Unprecedented process interactions are, therefore, likely not sufficiently represented. Moreover, the substantial simultaneous changes in forest ecosystems that may occur, such as climate change, nitrogen enrichment and the accelerated migration of potential pests as consequence of global trading of goods limits the opportunity to learn from the past. Field experiments are, therefore, important for constraining the modeling results and to indicate ecosystem responses to changing conditions that are not deductible from existing knowledge.

A challenge in climate change manipulation experiments is the size and longevity of mature forest ecosystems. One remedy is to focus on the compartments of the ecosystem that are considered to be particularly relevant. For the assessment of soil processes under conceivable warmer conditions, soil warming experiments have been set up in different forest ecosystems (Hagedorn et al. 2010; Jarvis and Linder 2000; Melillo et al. 2002; Schindlbacher et al. 2009). Their results are divergent with respect to the induced increase in CO_2 release from the soil. At some sites the increase in soil CO_2 emissions was transient and slowed down as the resource of easily decomposable SOM was exhausted. In other experiments warming elevated the CO_2 emissions from soils for many years. Another avenue of climate manipulation experiments is the reduction or exclusion of precipitation in order to simulate dryer conditions. Simulated drought strongly decreased the decomposition of SOM in temperate forests, whereas less to no effects on the soil CO_2 efflux were observed in the tropics (Davidson et al. 2008; Muhr and Borken 2009). In a temperate forest, the forest floor can become increasingly water repellent during drought and soil CO_2 emission were found to be substantially reduced for much longer as the actual drought lasted (Schindlbacher et al. 2012). Simultaneously, the uptake of C by tree-growth does not suffer during periods of reduced precipitation as tree roots can tap into deeper water saturated soil horizons. A combined warming-drought manipulation experiment showed that the increase in soil CO_2 emissions due to warming can be easily offset by the reduced soil CO_2 efflux during and after drought (Schindlbacher et al. 2012). The current trend towards multi-factorial climate manipulation experiments and attempts towards integrating the whole tree environment is a step forward to refine process related parameters in ecosystem models (Bronson et al. 2008; Niinistö et al. 2004). A universal manipulation experiment which includes changing climate parameters, increased atmospheric CO_2 levels and changes in nitrogen deposition in a mature forest has so far not been performed. It would challenge experimentalists technically and financially, but might be worth being conducted, as the compartments of forest ecosystems are closely interlinked and the total effect is not necessarily a linear combination of the individual effects. Such multi-factorial experiments need to be set up as parts of a long-term project, ideally extending beyond an entire rotation period (Fig. 6.4).

Another avenue of climate change experiments is the exposure of trees to elevated concentrations of CO_2. Several Free-Air-Carbon dioxide-Enrichment (FACE) experiments have often been conducted with young and vividly growing trees (Norby and Zak 2011). A maximum stimulation of tree growth occurred at concentrations up to 560 ppm unless other limiting factors such as water shortage and insufficient nutrient supply set in. For the long-term C sequestration potential of forest ecosystems the FACE experiments are not entirely relevant because the response to elevated CO_2 is probably transient (Körner et al. 2005).

Fig. 6.4 Automated chambers for the measurement of the soil carbon dioxide (*left*) and a roof to temporarily create drought conditions in a field experiment (*right*); Experimental site: mature, spruce-dominated forest, Mühleggerköpfl, Achenkirch, Tyrol (*Picture: Andreas Schindlbacher*)

6.3 Natural Disturbance of Forest Ecosystems

Complex ecosystems such as forests do not tend towards a state of equilibrium. Natural disturbances are part of forest ecosystem dynamics (Drever et al. 2006). The main disturbances in forests are the attack by damaging insects and pathogens, stand destruction by strong winds and snow, wildfire, and damages due to herbivores (Fig. 6.5). In an ecological context, disturbance is part of the natural forest dynamics, and the ability of an ecosystem to tolerate disturbances without undergoing fundamental changes is its "resilience" (Holling 1973). In regions of intensive forest management silviculture and harvesting has modified the natural disturbance patterns. Whether or not the frequency of natural disturbances is increasing and what factors are eventually responsible is subject to an ongoing debate. The available data on forest damages due to disturbance are by far less abundant than those due to harvest (Van Miegroet and Olsson 2011). The focus here is on disturbances caused by storm and insects. Fire is of regionally different relevance and the dynamics may be affected by many decades of fire suppression in actively managed forests (Certini 2005; Marañón Jiménez 2011).

6.3.1 Insects and Pathogens

Warmer site conditions and dry summers may accelerate the propagation rates of insects and pathogens, and also weaken host trees thereby increasing the susceptibility for attacks. Infestations by bark beetles, especially *Ips typographus* (L.), the dominant threat for Norway spruce forests in Central Europe, are projected to increase because under warmer conditions more generations by year develop (Wermelinger 2004). Especially vulnerable are secondary spruce forests, often established for economic reasons. The sites are often warmer than the ecological

Fig. 6.5 Natural disturbances are a part of ecosystem dynamics that are mostly excluded by active forest management; storm-damaged Norway spruce (*Picea abies* (L.) Karst.) forests in the High Tatra, Slovakia; the picture shows the situation in 2009, 5 years after the storm (*left*) and forest infested by bark beetle (*Ips typographus* L.) in Austria (*center*), burnt pine (*Pinus pinaster* L.) and (*P. nigra* L.) forests in the Sierra Nevada National Park, Spain. The Lanjarón wildfire occurred in 2005, the picture was taken in 2008 (*right*) (*Pictures: Magda Edwards, Christian Tomiczek and Sara Marañón Jiménez*)

Fig. 6.6 The Asian longhorned beetle; *Anoplophora glabripennis* (*left*), bark beetle; *Ips typographus* (*center*) and larva of the oak processionary; *Thaumetopoea processionea*, a moth (*right*) (*Pictures: Christian Tomiczek, Ute Tomiczek-Hoyer, Martin Brandstetter*)

optimum conditions for spruce. In addition, the global trading of wood and wood products facilitates the immigration of non-native insects and pathogens (Fig. 6.6). A prediction on the future pressure on forest trees is difficult but the concerns for more frequent epidemics are substantiated. The invasion of pathogens in new environments is not a novel process. The Dutch elm disease, caused by the ascomycete *Ophiostoma ulmi* (Buisman), and chestnut blight, caused by the fungus *Endothia parasitica* (Murr.), have afflicted tree populations in the United States and Europe in the past. The new challenge arises from the acceleration of these processes due to climate change and transcontinental transport of goods. Some thermophilic fungi that until now have been unproblematic are benefitting from warmer summers and infest trees more readily, summer droughts stress trees and make them more vulnerable to infection by fungi, and warmer winters may increase the activity of some weak pathogens, that are active only when the host is dormant (Lonsdale and Gibbs 2002). In addition, some fungi are performing host shifts that are believed to be a consequence of climate change (Gange et al. 2011). Moreover, the damage from insects needs to be seen in the context of storm damages. Mass propagations of insects are often observed when damaged forest stands are not immediately salvaged. The sufficiently moist stems are offering ideal breeding conditions for insects (Engesser et al. 2008; Hanewinkel et al. 2008).

Examples of a pressure from formerly not present beetles are the infestations of trees with the Asian longhorned beetle (*Anoplophora glabripennis*) and the Citrus longhorned beetle (*Anoplophora chinensis*). Both species are native to Asia and have been introduced into Europe mainly with packaging wood material and ornamental plants from China or other Asian countries. In Europe, the Asian longhorned beetle was first detected in the city of Braunau/Inn in Austria, the Citrus longhorned beetle in Parabiago/Italy (Tomiczek and Hoyer-Tomiczek 2007). In the meantime many infestations and interceptions are recorded all over Europe. At the beginning of the introduction most infestations occurred on park trees in cities. Later on both species showed that they were able to spread to forest stands. This fact was already known from Canada and the USA, where their uncontrolled spreading allowed to invade natural forest landscapes and alter the tree species composition (Dodds and Orwig 2011).

Dealing with an increased pressure from autochthonous and immigrating pathogens and insects requires a complex training of forest practitioners, more intensive efforts for monitoring of insect outbreaks, and the flexibility to quickly adopt countermeasures. For the sake of efficiency the monitoring needs to be trans-national to capture critical events. The global exchange of goods with wood as packaging material and trading of ornamental plants and their seeds is an additional potential vector for insects and pathogens and needs more attention and control.

A well described mass propagation is the outbreak of mountain pine beetle (*Dendroctonus ponderosae*) in British Columbia. Due to the low management intensity of the affected forests the human influence on the dynamics of the disturbance is considered to be minor. The suggestion that the outbreak was triggered by climate change was adopted (Kurz et al. 2008). The immediate effect of the high rate of tree mortality was that the forest sector that previously was a small sink of GHGs, turned into a large source. The forests became significant for the Canadian budget of GHG emissions.

6.3.2 Storm Damages

Records of forest damages indicate that European forests have been noticeable damaged by on average 2 storms by year in the last 60 years (Gardiner et al. 2010). Storm Bora affected 46 000 ha in the Tatra Mountains in 2004, storm Gudrun in 2005 was the strongest storm hitting Southern Sweden in 100 years, downing an equivalent of the total annual harvest of the country. Emma and Paula hit Central Europe in 2008 and many regions have there own history. These storms are responsible for more than 50 % of the abiotic and biotic damage that have been recorded in these years. The extent and location of storm damage and the vulnerability of individual forest stands depends on meteorological conditions, location, site properties, stand composition, and past forest management. Currently, no reliable forecasting tool for storm damages is available. Spruce and poplar (*Populus spp.*) forests have been most severely affected in the past, whereas oak forests were damaged to a lesser degree. The projected future frequency of extreme events and eventual changes in the increase in frequency and severity of storms is controversially discussed, but a southward shift of storm activities is predicted by models (Ulbrich et al. 2009). In European forests the increased standing stock of trees and average forest age has contributed to forest damages (Gardiner et al. 2010; Jonášová et al. 2010; Schmidt et al. 2010; Seidl et al. 2011b).

Practical forestry can adapt to the problem of storm damages by proactive silviculture and knowledge is documented in classic textbooks of forestry (Assmann 1961; Mayer 1984; Oliver and Larsen 1990). Mixed-species forests are generally understood to withstand storms better than mono-species stands, early thinning interventions ensure the development of a favorable tree-height/stem-diameter ratio, and short rotation periods allow to harvest forests that later in their life cycle would become more vulnerable to storm damages. These silvicultural strategies have limits and even ideally managed stands cannot withstand extreme storm events. Once storms have damaged a part of forest the potential for further damages in subsequent events is high. It is often observed that an initial event opens the forest canopy and from the exposed edge of the stand the damaged area propagates into the stand and finally affects a larger area.

6.3.3 Human Influence

Climate change is occurring at a time when natural environments are becoming increasingly fragmented through habitat destruction, and when species are being moved inadvertently or deliberately around the globe at ever increasing rates. This means that climate change is occurring at a time when many forest ecosystems are already under pressure from invading species and disturbances. Fragmentation and invasions may also affect evolutionary processes by changing the way genes move around landscapes and by introducing novel genotypes into populations through hybridization (Hoffmann and Sgrò 2011).

Increased occurrences of disturbances are often linked to climate change and forest practitioners are willing to attribute unfavorable processes to it. However, storm damages have a long history in Central Europe. Already more than a century ago it was shown that secondary spruce forests were particularly vulnerable. The proposed remedy of establishing mixed-species forests has not always been adopted and the high production risk of a spruce-dominated forestry was obviously accepted for economic reasons (Assmann 1961). More recently, Central European forests have been subject to changes that occurred concurrent with global change. The stand density and the average stand age has increased because low timber prices made a proactive form of forest management unattractive. At the same time,

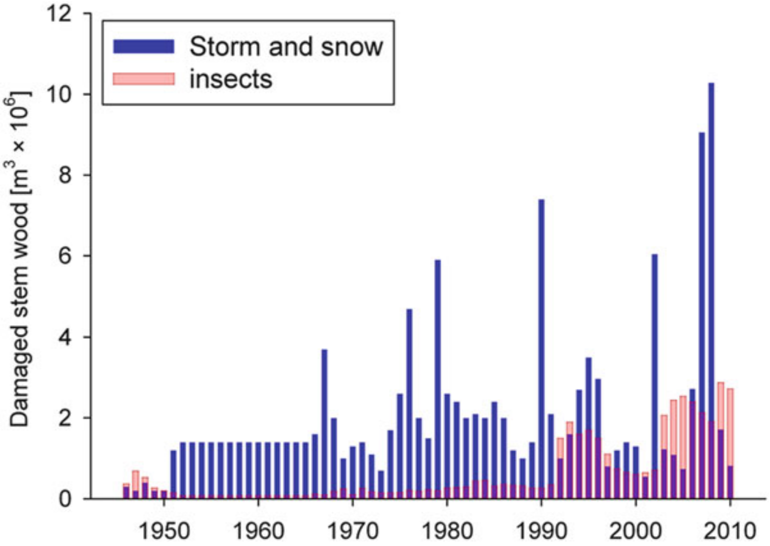

Fig. 6.7 Damaged stem wood volume in Austrian forests from 1946 to 2010. Storm and snow damages show an irregular pattern, damages caused by insects attacks are increasing. Bark beetle (*Ips typographus*) are the main cause for the insect damages (Data: *Christian Tomiczek*)

the growth rate has been increasing and nitrogen enrichment has been playing an important role (Sutton et al. 2011). Forests grew denser and higher and were more vulnerable to storm damage. Economical constraints in forest management led to decreasing monitoring efforts for insect-caused damages. Especially in areas with single-species forests large-scale insect outbreaks were observed. In a detailed study on reported forest damages in European forests it was identified that both storm and insect damages are enhanced by climate change as well as by management changes. The causes for wildfires were more difficult to disentangle due to insufficient data (Seidl et al. 2011b). The negative consequence is that forests are under increasing pressure. A positive aspect is that appropriate forest management strategies can alleviate the pressure partially.

An example for damages due to disturbances for Austrian forests is shown in Fig. 6.7. Storms and snow damages show the expected irregular temporal pattern because they are caused by singular extreme and rare climatic events. Quite typically, insect damages follow because the damaged timber is often not processed in time and is an ideal breeding ground for bark beetles. Bark beetle is indeed the by far dominating insect causing damage to Norway spruce forests. The figure displays the complete reliable record of forest damages in Austria and gives disconcerting evidence that damages due to bark beetle are no longer decreasing to pre-disturbance levels. Since the early 1990s, the insect-related damages are showing an upward trend. Apparently, the permanent stock of bark beetle is gradually increasing.

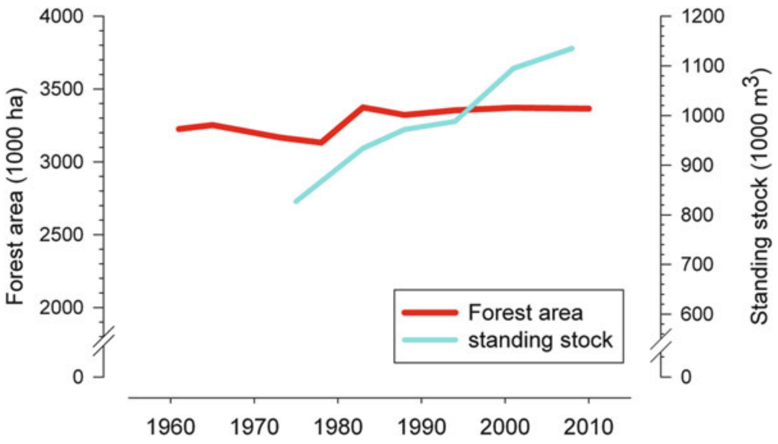

Fig. 6.8 Change of the forest area and the standing stock of stem biomass in Austrian forests from 1961 to 2010 (Data: Austrian Forest Inventory, http://bfw.ac.at/rz/bfwcms.web?dok=4303)

Central European foresters are successfully following the principles of sustainable forest management. The term encompasses a balanced form of forest management that ensure the provision of several forest functions under conditions of temporally differing demands for different forest products. The Ministerial Conference on the Protection of Forests in Europe offered a definition for sustainable forest management (MCPFE 2003):

> The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.

An example for the variable meaning of sustainability is shown in Fig. 6.8 for Austrian forests. Forest inventory data indicate that the forest area is slowly and significantly increasing, mostly due to the afforestation of marginal agricultural land. The standing stock increases at a higher rate. Reasons are the increased forest productivity due to nitrogen enrichment and the elongation of the growing season and the increase in stand age (Schadauer 1996; van Oijen and Jandl 2004). The low timber prices have given little incentives to harvest at the same rate as forests have been incrementing and the average stand age has increased. Despite substantial changes in the forests, forest management at any time during the last five decades may have been considered to be an example of sustainable management. Deriving a sustainable harvest rate yields 280 m^3 stem wood for the inventory conducted between 1986 and 1990 and 325 m^3 for the inventory period 2007–2009 (Russ 2011; Büchsenmeister 2011). In just one decade the amount of sustainably extractable timber would have increased by more than 15 % although the observed changes in the forested landscape would have been subtle and hardly detectable.

6.4 Adaptive Forest Management

The term ‘adaptive management’ was coined by Buzz Holling and encompasses the organization of the implementation of a forest management strategy in a series of alternating workshops and research periods. Adaptive management gives the opportunity of reviewing and modifying opinions and developing options for stakeholders and policy makers (Holling 1978). The concept ensures that the elaborated adaptive assessment and management develops as it proceeds. The approach surveys the features of the environment likely to be affected by the developments under consideration, analyses the information collected, tries to predict the impact of these developments and lays down guidelines or rules for their management. Upon completion of the process, managers receive well-articulated management plans and then monitoring begins in order to later evaluate the management plans.

Forest managers need to address climate change issues because, without action, some of the foreseeable impacts of climate change on forest ecosystems and their ecosystem services are socially inacceptable. Considering the role that forests play on the provision of water, hydropower, protection against natural hazards, it is difficult to imagine the establishment of technical structures, capable of resplacing forests (Beniston et al. 2011). Adaptation measures should either decrease the probability of damage triggered by climate change, identify upcoming opportunities associated with climate change, or increase the resilience of forests. Unsuitable forms of adaptive forest management bear the risk of economic losses, and may compromise the provision of ecosystem services.

6.4.1 Tools

Since more than 20 years forest growth models of different scales (tree level to entire watersheds) have been developed (Weiskittel et al. 2011). Earlier, the drivers of these models were based on steric interactions such as competition between trees for light or nutrients. New models focus on the integration of climate as stressor or catalyst, on species competition, and on ecosystem disturbances. Current research in mountain forest management is focusing on predicting impacts of future climates on forest growth and tree migration, using simulation models and assuming different climate scenarios. Another group of the models used are “management models” where the emphasis is on the description of competition between trees and the growth performance of different species. Another group of models are “succession models” emphasizing the regeneration of particular tree species under changing site conditions (Fig. 6.9). These simulations compare different adaptive forest management strategies. Ideally, such simulations of the productivity of forests are coupled with simulations of the SOC pool. An emerging challenge is the coupling of forest growth models, simulations of natural hazard propagation, and climatic and

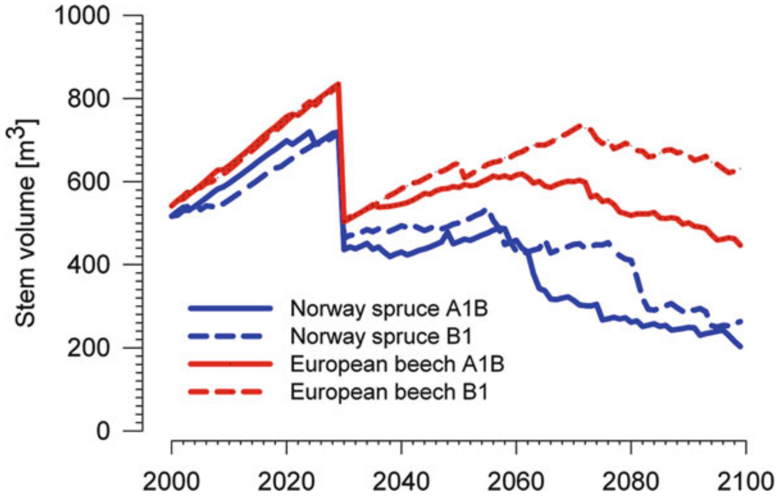

Fig. 6.9 Simulated growth of Norway spruce and European beech under the same management intensities and the site conditions of the Ossiach region in Southern Austria and the IPCC climate scenarios A1B and B1 from 2000 to 2100. The simulation indicates that the climate conditions of A1B are less favorable than B1. The growth performance of Norway spruce is stronger affected by climate change than European beech (*Data: Robert Jandl*)

socio-economical models. Such complex model ensembles enable the comprehensive analysis of strategies of adaptive forest management. The concepts of resistance, resilience and viability of ecosystems and of ecosystem functions have been improved via the use of models. Research increasingly tries to integrate the large uncertainty in how the climate and the timber market will develop, and how the demand for ecosystem services will evolve.

Another important set of information comes from forest management guidelines. Often, those are referring to existing site conditions and it is up to the forest practitioner to draw conclusions on the validity of the concepts under future conditions. The existing guidelines are often geared towards the forestry community of a specific region. Examples are available for Austrian and Swiss forests (Amann et al. 2010; Rigling et al. 2008). The texts are often not translated into English because they have a specific target audience.

An exemplary life cycle of the development of a concept of adaptive management consists of numerous elements. They are the assessment of the present forest management concept, projection of the future stand development, definition of indicators for sustainable forestry, evaluation of the foreseeable vulnerability based on defined indicators, development of future forest management with the intention of reducing the vulnerability. A decisive step is the interaction with stakeholders and the assessment whether the chosen concept of adaptive management performs well (Heinimann 2010; Seidl et al. 2011a).

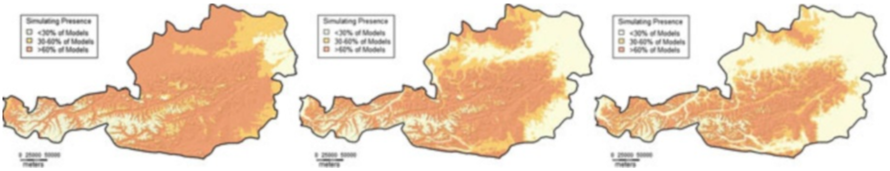

Fig. 6.10 Predicted occurrence of Norway spruce (*Picea abies*) in Austria. The *graph* shows the agreement of an ensemble of simulation models; present occurrence (*left*), predicted occurrence from 2020 until 2050 (*center*), and predicted occurrence from 2050 until 2080 (*right*) (*Figure: courtesy of Niklaus Zimmermann, WSL*)

6.4.2 Tree Species Selection

Adaptation may be an important strategy for natural populations to cope with rapid climate change. Threatened species can persist if they are unable to disperse naturally or through human-mediated translocation to climatically more suitable habitats. This process may also be essential in the case of dominant conifers being attacked by bark beetle populations benefiting from warming conditions. Any adaptation of tree species comes at a cost. It has been shown for birch (*Betula spp.*) and Scots pine that high mortality is able to reduce the adaptation lag between tree populations and the changing climatical optimum. However, adaptation cannot keep up when the environmental change occurs too quickly (Hoffmann and Sgrò 2011). Increasing periods of thermal stress and drought will produce a directional selection for resistance, particularly for species close to their physiological limits. An option to evaluate the ability of tree species in coping with future conditions is the use of *climate envelopes*. In its simplest case, climate envelopes are two-dimensional presence/absence graphs of tree species, derived from large data sets such as national forest inventories with the mean annual temperature and the precipitation as axes. More elaborate evaluations also take into account the influence of present and projected climate extremes and the competition between tree species. An ensemble of model consisting of different climate scenarios and projections of site conditions shows the current and predicted habitat of Norway spruce in Austria (Zimmermann et al. 2009) (Fig. 6.10). Presently, spruce is the dominant tree species. Only the summer-warm region in the east of Austria and the high-elevation zones in the Alps are not suitable for spruce. According to the simulations spruce will gain small areas in high mountains but will lose substantially in lower elevations. Even when scrutinizing the validity of the models the projections raise doubts that a business-as-usual scenario for forest management is justified.

One option of adaptive forest management is re-considering the list of managed tree species. Further, the debate continues whether drawing a distinction between "native" and "non-native" species helps in analysing the factors that affect species change. A potential issue with new tree species is that it is highly uncertain how they deal with new site conditions during an entire rotation cycle. It has been shown that some species do very well in a new environment because they escape their enemies when moving or being forced to move to a new range (Pyšek et al. 2009; Reif et al. 2011). The combination of release from enemies and inherent growth ability produces a synergistic effect that explains patterns seen in the abundance and types of invaders, and in the patterns of invasion seen in many ecosystems (Blumenthal et al. 2009; Seastedt 2009). Due to its high productivity and tolerance towards summer drought, the coast Douglas fir (*Pseudotsuga menziesii* var. *menziesii*) that is naturally not occurring in Central Europe is discussed as alternative to European beech. In Bavaria, Douglas fir covers only 0.7 % of the forest area but plans exist to increase it to 3 % in the next 50 years. It has been studied that mixtures of Douglas fir with other species are possible in order to maximize the delivery of ecosystem services such as timber production and C sequestration (Prietzel and Bachmann 2012). The displayed unsuitability of low-elevation sites for Norway spruce in Austria, as indicated by Fig. 6.10, raises doubts whether native tree species will be able to replace Norway spruce in future commercial forests. The potential natural tree species composition is useful as a reference state for the next decades but may fail for an entire rotation period.

There are ecosystems where the flexibility with respect to tree species is rather narrow. Many mountain forests in the Alps are protecting infrastructures and settlements. Often it is required that the protective function is permanently ensured. A long history of silviculture has shown some optimal tree species combinations and stand structures (Mayer 1976). In continental inneralpine valleys the dominant tree is Norway spruce whereas Cembran pine (*Pinus cembra*) forms the timberline. Presently, there is no known option to introduce tree species that have a similar year-round protective function similar to spruce.

The establishment of mixed-species forests is an integral part of concepts for adaptive forest management. It implies that different species are occupying different ecological niches. Upon a threat to the forest the risk is distributed over several species of different vulnerabilities. Even when one species is strongly affected or killed, a sufficient number of trees and tree species may survive. Thus, it is possible to continue with forest management and the positive effect of soil protection by the forest is ensured. In forest ecology mixed-species forests have been offered as a solution (Mayer 1984; Oliver and Larsen 1990; Puettmann et al. 2009). They have been recommended as remedy against acid rain, biodiversity loss, soil acidification and now as solution against adverse effects of climate change. A positive effect of mixed-species forests is that they allow considering the uncertainty of future site conditions. A mixture of tree species can exploit the nutrient and soil moisture pool of soil profiles better than a mono-species tree stand. The differences in rooting patterns among species stabilize the forest and make it more stable against storm damage. Moreover, new invading insects are expected to have a preference for particular species and may destroy single-species stands more easily than mixed-species stands. Overall, mixed-species stands are expected to offer a higher stability than single-species stands and are, therefore, superior when facing the threats of climate change.

In many European regions the forests are under pressure from a high animal population density. In Central Europe ungulates cause substantial damage to forests, but insufficient countermeasures are taken in many regions because the objectives of the hunting communities is not aligned with forest management. The selective browsing by deer in Central European forests inhibits the development of additional stand-stabilizing tree species and the entire discussion on the benefits of mixed-species forests remains futile. A potential remedy is fencing the newly establishing forests in order to offer protection in the early phase of stand development. However, fencing is expensive and not popular with a society that is entitled to access forests for recreation (Schulze and Schulze 2010).

6.4.3 Silviculture

Current research in forest management is focusing on predicting impacts of future climates on forest growth and tree migration, using simulation models and assuming different climate scenarios. These simulations serve to compare different adaptive forest management strategies. The simulation outcomes are associated with high uncertainties. However, uncertainty is not an excuse for not to act. Research projects integrate the large uncertainty in the interaction between climate change, timber market, and the demand for ecosystem services. Following the principles of adaptive management the collection of expertise from numerous stakeholders such as local forestry experts is required. In this participatory process we have to keep in mind that the future forest conditions may not be deductable from past forest dynamics, considering that numerous processes are changing simultaneously and taking into account that the present and future climate and – as a consequence of elevated rates of nitrogen input – trophic conditions may be unprecedented at many sites (Butterbach-Bahl et al. 2011; Sutton et al. 2011).

Considering the duration for silvicultural adaptation measures the window to a successful adaptation of forest management to climate change successively narrows. When establishing a new forest stand it is required to think about 100 years ahead and to evaluate the suitability of tree species for the entire rotation period. When adaptation to increased insect pressure is required the existing management concepts may be still appropriate even when the monitoring and intervention frequency needs to increase.

The age of forests and the management intensity play an important role on the C stock. Old-growth forests serve as a reference systems for the C retention under site conditions. The dominating position is that old-growth forests have maximum C stocks but negligible stock changes averaged over a region because inputs and losses are in close equilibrium (Franklin et al. 2002; Harmon 2001). The paradigm of zero-stock changes over time has recently been challenged and unexpected productivity rates of mature forests and ongoing increases in the SOC stock have been detected (Luyssaert et al. 2008; Zhou et al. 2006). Consequently a line of argumentation was opened in favor of discontinuing forest management in order to benefit both from maximized C stocks and long-term increases. The concept, however, falls short in accounting for avoided emissions due to different products of forest management (wood products, renewable energy). Sustainable forest management ensures ideally a neutral C cycle on forest land. Wood products can substitute for other goods that would be built from non-renewable materials. The biomass from forests is an important provider of bioenergy. Maintaining the stability of forest stands requires silvicultural interventions whose costs are covered by the revenue from timber sales (Malmsheimer et al. 2011).

6.4.3.1 Afforestation

The question of the choice of tree species propagates into the topic of establishing new forests. When natural regeneration is the method of choice the forest managers opts for maintaining the list of existing tree species and potentially accepting shifting dominances of the species. When strong doubts on the suitability of tree species in a future climate prevail, it may be wise to artificially regenerate stands with afforestation programmes. Such decisions can only be made on the basis of thoroughly established knowledge because errors will turn out costly. In the case that the traditional tree species cannot cope with future climate conditions the follow up costs of required silvicultural interventions and eventually a premature harvesting of the forest will hardly be covered by revenues from timber sale. Alternatively, establishing a costly afforestation even when the traditional tree species would have been successful represents an unnecessary expense. In addition to complete species shifts, afforestation measures might also be implemented to increase the number of tree species and to establish mixed-species forests. In particular, secondary conifer forests often consist of only a few tree species. Mixed-species forest – containing species with high and low risks under future climate conditions – are seen as a viable alternative because the uncertain future risk is proactively addressed and the present strategy of timber production is maintained.

6.4.3.2 Provenances

As another measure to maintain existing forest ecosystems, the planting of different provenances of the same tree species has been suggested (Matyas 1996; Rehfeldt et al. 1999). Up to now, the utilization of local seed sources for reforestation has been regarded as the most efficient way to avoid maladaptation under prevailing environmental conditions. However, for the changing climate recent analyses of provenance tests suggest that seed transfer from well adapted populations or populations with a particularly high potential for adaptation to the expected climate conditions can facilitate the maintenance of the productivity and vitality of presently used tree species (Kapeller et al. 2012; O’Neill et al. 2008; Wang et al. 2006). Although forest trees are sedentary and long-living organisms that have evolutionary developed means to adapt to changing conditions, a number of recent publications

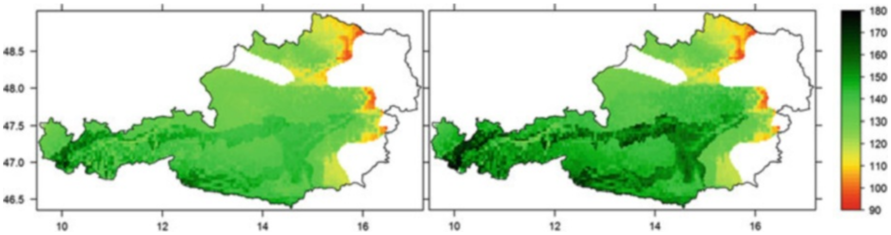

Fig. 6.11 Map of Norway spruce productivity within the current natural distribution range in Austria. The colors indicates the percental change of estimated tree heights from current conditions until the 2080s given that (**a**) local seed material of respective national provenance regions are used (*left*) or (**b**) seed material of the best performing population clusters are used (*right*) (*Data: Silvio Schüler*) (Color figure online)

corroborate the assumption that natural adaptation or range shifts may be too slow to keep up with the speed of climate change (Petit et al. 2008; Savolainen et al. 2007). A recent analysis of a large Austrian provenance test confirmed the impact of provenance selection for forest productivity in the future (Kapeller et al. 2012). The test series comprised tree height data of Norway spruce at the age of 15 years from 379 populations planted at 29 test sites across Austria. Connecting these data to climate information of the test sites and the provenance origin helps to calibrate climate response functions for groups of Norway spruce populations and to estimate the future productivity for a regionalized A1B scenario. Generally, the study did not reveal any declines in employed proxies for productivity throughout the current distribution range of Norway spruce in Austria. For most parts of Austria an increase of tree heights up to 45 % can be expected until 2080. However, the impact of a warming climate is different for individual population groups. Variation in climate response increases with higher temperatures and less precipitation. Thus, an optimized choice of seed material according to prospective future climate conditions has the potential for an additional increase of productivity up to 11 % (Fig. 6.11). The intra-specific variation in climate response can be explained by the local adaptation of provenances (Kapeller et al. 2012).

6.5 Conclusions

Due to the potential of forests for mitigating climate change the public attention on forest management has been rising considerably. Society expects that forests provide simultaneously numerous ecosystem services and the maintenance of high C stocks ranks high on the agenda. Forests store C in both the tree biomass and in the soils. Given that forests annually exchange about sevenfold more CO_2 with the atmosphere by photosynthesis and respiration than is emitted by burning of fossil fuels, the role of forests in the global C cycle is significant. However, forests are not a solution to climate change effects and do not interfere with the responsibility of reducing the anthropogenic emission of GHGs. A mere conservation of forest land can ensure the maintenance of a large C pool in terrestrial ecosystems. However, global population growth and increasing demands for food, feed, fuel and fibre exert increasing pressures on forest ecosystems. Particularly in developing countries and countries with economies in transition the pressure towards converting pristine forests to agricultural land is high. The establishment of a legal basis of forest protection and the enforcement of Forest Acts shows promising signals towards slowing the rate of the deforestation. In developed nations, the forest area is often increasing because marginal agricultural land is either actively afforested or encroached by shrubs and trees.

Forests themselves are vulnerable to climate change. Rapid warming and a change in the hydrological regime modifies site conditions. Forests may no longer be able to inhabit some areas because the site conditions are detoriating, but may be able to expand into lands that were so far not forested. For a successful migration of forests it is required that the changes are occurring rather slowly. An immediate effect of climate change is the migration of pests and pathogens. Their pressure on forests is already increasing. High uncertainty prevails on the relevance of changes in the frequency of extreme climatic events. The available data on increased frequencies of flooding, extreme precipitation events, storms and droughts are uncertain. However, when managing forest stand with rotation periods of several decades a cautious foresight needs to take into account climate dynamics that are likely, even when not yet statistically significant.

Forest practitioners can use many tools for “adaptive forest management”. Simulation models parameterized with climate scenarios allow the visualisation of likely future forest conditions under chosen management scenarios, climate envelopes for tree species give indications on the expected shift of the potential habitat of trees. Silvicultural methods allow the creation of stable forests that are considered to withstand pressures efficiently. A successful concept is the establishment of mixed-species forests because the tree species have different abilities to tolerate stressors. The increased pressure from pests and pathogens both due to climate change and the global exchange of woody material calls for increased and transnational monitoring efforts in order not be caught by surprise by insect outbreaks. Another field is the choice of tree species. In a future climate the present distribution of tree species cannot be maintained. Remedies are the focus on other species or the selection of provenances that are expected to cope with future conditions.

Climate change is easily called upon as the reason for undesired dynamics of forest ecosystems. However, many forests have undergone recent changes that are unrelated to climate change. An example is the forestry in Central Europe. For several decades the harvest rates were lower than the annual increment. In consequence, forest grew older and denser and were, therefore, more vulnerable to storm damages. It is still disputed whether the frequency and severity of storms is increasing. In the last decades the response of forest practitioners to outbreaks of bark beetles were not sufficiently efficient and mass propagations caused substantial damages. An example for the Mediterranean region is the increase in forest fires.

Besides climate change, contributing factors are higher forest stand densities and a direct human influence. The conclusion is that the potential effects of forst management to decrease the vulnerability of forst stands has not yet been fully exploited and that adaptive forest management can play an important role for the forestry sector.

Setting aside forests for the sake of maximizing the C pool in the biomass and the forest soil is not seen as a successful concept of sustainable forest management. Unmanaged forests can only saturate the C pool once. Actively and sustainably managed forests are representing large C pools as well and can, in addition, provide wood products that replace other forms of construction materials, and can generate biomass as a renewable form of energy.

Acknowledgements This paper is an output of the project, Management strategies to adapt Alpine Space forests to climate change risks (MANFRED), as part of the EU Interreg Alpine Space Programme. The data for the climate envelope of Norway spruce are derived from the Austrian National Forest Inventory and were evaluated by Nik Zimmermann, WSL, Switzerland.

References

Amann G, Schennach R, Kessler J, Maier B, Terzer S (2010) Handbuch der Vorarlberger Waldgesellschaften – Gesellschaftsbeschreibungen und waldbaulicher Leitfaden. Landesregierung Vorarlberg

Anderson RG, Canadell JG, Randerson JT, Jackson RB, Hungate BA, Baldocchi DD, Ban-Weiss GA, Bonan GB, Caldeira K, Cao L, Diffenbaugh NS, Gurney KR, Kueppers LM, Law BE, Luyssaert S, O'Halloran TL (2010) Biophysical considerations in forestry for climate protection. Front Ecol Environ 9(3):174–182

Assmann E (1961) Waldertragskunde – Organische Produktion, Struktur, Zuwachs und Ertrag von Waldbeständen. BLV Verlagsgesellschaft, München

Baldocchi DD (2003) Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob Change Biol 9:479–492

Beck W (2010) Auswirkungen von Trockenheit und Hitze auf den Waldzustand in Deutschland – waldwachstumskundliche Ergebnisse der Studie im Auftrag des BMEL. In: DVFFA– Sektion Ertragskunde, Jahrestagung, 2010

Beniston M, Stoffel M, Hill M (2011) Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European ACQWA project. Environ Sci Policy 14(7):734–743

Blumenthal D, Mitchell CE, Pyšek P, Jarošík V (2009) Synergy between pathogen release and resource availability in plant invasion. Proc Natl Acad Sci U S A 106(19):7899–7904

Bonan GB (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320:1444–1449

Bronson DR, Gower ST, Tanner M, Linder S, Van Herk I (2008) Response of soil surface CO_2 flux in a boreal forest to ecosystem warming. Glob Change Biol 14:856–867

Büchsenmeister R (2011) Waldinventur 2007/09: Betriebe und Bundesforste nutzen mehr als den Zuwachs. BFW-Praxisinformation 24:6–9

Butterbach-Bahl K, Nemitz E, Zaehle S (2011) Nitrogen as a threat to the European greenhouse balance. In: The European nitrogen assessment, chap 19. Cambridge University Press, Cambridge, pp 434–462

Calfapietra C, Ainsworth EA, Beier C, Angelis PD, Ellsworth DS, Godbold DL, Hendrey GR, Hickler T, Hoosbeek MR, Karnosky DF, King J, Körner C, Leakey AD, Lewin KF, Liberloo M, Long SP, Lukac M, Matyssek R, Miglietta F, Nagy J, Norby RJ, Oren R, Percy KE, Rogers A, Mugnozza GS, Stitt M, Taylor G, Ceulemans R (2010) Challenges in elevated CO_2 experiments on forests. Trends Plant Sci 15(1):5–10

Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia 143:1–10

Ciais P, Reichstein M, Viovy N, Granier A, Ogé J, Allard V, Aubinet M, Buchmann N, Bernhofer C, Carrara A, Chevallier F, Noblet ND, Friend AD, Friedlingstein P, Grünwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Loustau D, Manca G, Matteucci G, Miglietta F, Ourcival JM, Papale D, Pilegaard K, Rambal S, Seufert G, Soussana JF, Sanz MJ, Schulze ED, Vesala T, Valentini R (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529–533

Davidson E, Nepstad D, Yoko Ishida F, Brando P (2008) Effects of an experimental drought and recovery on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest. Glob Change Biol 14:2582–2590

Denman K, Brasseur G, Chidthaisong A, Ciais P, Cox P, Dickinson R, Hauglustaine D, Heinze C, Holland E, Jacob D, Lohmann U, Ramachandran S, da Silva Dias P, Wofsy S, Zhang X (2007) Couplings between changes in the climate system and biogeochemistry. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK/New York, pp 500–587

Dixon R, Brown S, Houghton R, Solomon A, Trexler M, Wisniewski J (1994) Carbon pools and flux of global forest ecosystems. Science 263:185–190

Dodds KJ, Orwig DA (2011) An invasive urban forest pest invades natural environments – Asian longhorned beetle in northeastern US hardwood forests. Can J For Res 41(9):1729–1742

Don A, Schumacher J, Freibauer A (2011) Impact of tropical land-use change on soil organic carbon stocks? A meta-analysis. Global Change Biol 17(4):1658–1670

Drever CR, Peterson G, Messier C, Bergeron Y, Flannigan M (2006) Can forest management based on natural disturbances maintain ecological resilience? Can J For Res 36(9):2285–2299

Eglin T, Ciais P, Piao SL, Barre P, Bellassen V, Cadule P, Chenu C, Gasser T, Koven C, Reichstein M, Smith P (2010) Historical and future perspectives of global soil carbon response to climate and land-use changes. Tellus B 62(5):700–718

Engesser R, Forster B, Meier F, Wermlinger B (2008) Forstliche Schadorganismen im Zeichen des Klimawandels. Schweiz Z For 159(10):344–351

Enquist BJ, Niklas KJ (2002) Global allocation rules for patterns of biomass partitioning in seed plants. Science 295:1517–1520

Food and Agricultural Organization of the United Nations (ed) (2006) Global forest resources assessment 2005. Progress towards sustainable forest management, FAO forestry papers, vol 147. FAO, Rome

Franklin JF, Spies TA, Pelt RV, Carey AB, Thornburgh DA, Berg DR, Lindenmayer DB, Harmon ME, Keeton WS, Shaw DC, Bible K, Chen J (2002) Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. For Ecol Manage 155:399–423

Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, Brovkin V, Cadule P, Doney S, Eby M, Fung I, Bala G, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler KG, Schnur R, Strassmann K, Weaver AJ, Yoshikawa C, Zeng N (2006) Climate-carbon cycle feedback analysis: results from the C^4MIP model intercomparison. J Clim 19:3337–3353

Friedlingstein P, Houghton RA, Marland G, Hackler J, Boden TA, Conway TJ, Canadell JG, Raupach MR, Ciais P, Quéré CL (2010) Update on CO_2 emissions. Nat Geosci 3:811–812

Führer E (2000) Forest functions, ecosystem stability and management. For Ecol Manage 132:29–38

Gange AC, Gange EG, Mohammad AB, Boddy L (2011) Host shifts in fungi caused by climate change? Fungal Ecol 4(2):184–190

Gardiner B, Blennow K, Carnus JM, Fleischer P, Ingemarson F, Landmann G, Lindner M, Marzano M, Nicoll B, Orazio C, Peyron JL, Reviron MP, Schelhaas MJ, Schuck A, Spielmann M, Usbeck T (2010) Destructive storms in European forests: past and forthcoming impacts. EFI, Joensuu

Hagedorn F, Martin M, Rixen C, Rusch S, Bebi P, Zürcher A, Siegwolf RTW, Wipf S, Escape C, Roy J, Hättenschwiler S (2010) Short-term responses of ecosystem carbon fluxes to experimental soil warming at the Swiss alpine treeline. Biogeochemistry 97:7–19

Hanewinkel M, Breidenbach J, Neeff T, Kublin E (2008) Seventy-seven years of natural disturbances in a mountain forest area – the influence of storm, snow, and insect damage analysed with a long-term time series. Can J For Res 38(8):2249–2261

Harmon ME (2001) Carbon sequestration in forests. J For 4:24–29

Heimann M, Reichstein M (2008) Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature 451:289–292

Heinimann HR (2010) A concept in adaptive ecosystem management–an engineering perspective. For Ecol Manage 259(4):848–856

Hoffmann AA, Sgrò CM (2011) Climate change and evolutionary adaptation. Nature 470:479–486

Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 4:1–23

Holling CB (1978) Adaptive environmental assessment and management. John Wiley & Sons, London

Houghton R (2008) Carbon flux to the atmosphere from land-use changes: 1850–2005. Trends: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, USA

IPCC (2011) Summary for policymakers. In: Intergovernmental Panel on Climate Change special report on managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge University Press, Cambridge, UK/New York

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK/New York

Jarvis P, Linder S (2000) Constraints to growth of boreal forests. Nature 405:904–905

Jonášová M, Vávrová E, Cudlín P (2010) Western Carpathian mountain spruce forest after a windthrow: natural regeneration in cleared and uncleared areas. For Ecol Manage 259(6):1127–1134

Kapeller S, Lexer MJ, Geburek T, Hiebl J, Schueler S (2012) Intraspecific variation in climate response of Norway spruce in the eastern alpine range: selecting appropriate provenances for future climate. For Ecol Manage 271:46–57

Kaplan JO, Krumhardt KM, Zimmermann N (2009) The prehistoric and preindustrial deforestation of Europe. Quat Sci Rev 28(27–28):3016–3034

Karhu K, Wall A, Vanhala P, Liski J, Esala M, Regina K (2011) Effects of afforestation and deforestation on boreal soil carbon stocks – comparison of measured C stocks with Yasso07 model results. Geoderma 164(1–2):33–45

Körner C (2003) Slow in, rapid out – carbon flux studies and Kyoto targets. Science 300:1242–1243

Körner C, Asshoff R, Bignucolo O, Hättenschwiler S, Keel SG, Peláez-Riedl S, Pepin S, Siegwolf RTW, Zotz G (2005) Carbon flux and growth in mature deciduous forest trees exposed to elevated CO_2. Science 309:1360–1363

Kump LR (2011) The last great global warming. Sci Am 7:57–61

Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L (2008) Mountain pine beetle and forest carbon feedback to climate change. Nature 452:987–990

Kurz W, Dymond C, White T, Stinson G, Shaw C, Rampley G, Smyth C, Simpson B, Neilson E, Trofymow J, Metsaranta J, Apps M (2009) CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol Model 220(4):480–504

Laganière J, Angers DA, Paré D (2010) Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Glob Change Biol 16(1):439–453

Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster P, Friedlingstein P, Gurney K, Houghton RA, House JI, Huntingford C, Levy PE, Lomas MR, Majkut J, Metzl N, Ometto JP, Peters GP, Prentice IC, Randerson JT, Running SW, Sarmiento JL, Schuster U, Sitch S, Takahashi T, Viovy N, van der Werf GR, Woodward FI (2009) Trends in the sources and sinks of carbon dioxide. Nat Geosci 2:831–836

Lindner M, Karjalainen T (2007) Carbon inventory methods and carbon mitigation potentials of forests in Europe: a short review of recent progress. Eur J For Res 126:149–156

Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ, Marchetti M (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manage 259(4):698–709

Lonsdale D, Gibbs J (2002) Effects of climate change on fungal diseases of trees, Bulletin, vol 125, chap 7. Forestry Commission Publications, Stockport

Lüthi D, Le Floch M, Bereiter B, Blunier T, Barnola JM, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K, Stocker TF (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453:379–382

Luyssaert S, Schulze ED, Börner A, Knohl A, Hessenmöller D, Law BE, Ciais P, Grace J (2008) Old-growth forests as global carbon sinks. Nature 455:214–215

Luyssaert S, Ciais P, Piao SL, Schulze ED, Jung M, Zaehle S, Schelhaas MJ, Reichstein M, Churkina G, Papale D, Abril G, Beer C, Grace J, Loustau D, Matteucci G, Magnani F, Nabuurs GJ, Verbeeck H, Sulkava M, Van Der Werf GR, Janssens IA, Members of the CARBOEUROPE-IP SYNTHESIS TEAM (2010) The European carbon balance. Part 3: forests. Glob Change Biol 16(5):1429–1450

Malmsheimer R, Bowyer J, Fried J, Gee E, Izlar R, Miner R, Munn I, Oneil E, Stewart W (2011) Managing forests because carbon matters: integrating energy, products, and land management policy. J For (Suppl) 109(75):S7–S51

Marañón Jiménez S (2011) Efecto del manejo de la madera quemada después de un incendio sobre el ciclo del carbono y nutrientes en un ecosistema de montaña mediterránea. PhD thesis, Universidad de Granada

Mather A, Needle C (1998) The forest transition: a theoretical basis. Area 30(2):117–124

Matyas C (1996) Climatic adaptation of trees: rediscovering provenance tests. Euphytica 92:45–54

Mayer H (1976) Gebirgswaldbau – Schutzwaldpflege. Gustav Fischer, Stuttgart

Mayer H (1984) Waldbau auf soziologisch-ökologischer Grundlage. G. Fischer, Stuttgart

MCPFE (2003) Ministerial conference on the protection of forests in Europe. Improved pan-European indicators for sustainable forest management as adopted by the MCPFE expert level meeting, 7–8 Oct 2002, Vienna. http://www.foresteurope.org/documentos/improved_indicators.pdf

Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ, Allen MR (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458. doi:10.1038/nature0801

Melillo J, Steudler P, Aber J, Newkirk K, Lux H, Bowles F, Catricala C, Magill A, Ahrens T, Morrisseau S (2002) Soil warming and carbon-cycle. Feedbacks to the climate system. Science 298:2173–2176

Muhr J, Borken W (2009) Delayed recovery of soil respiration after wetting of dry soil further reduces C losses from a Norway spruce forest soil. J Geophy Res 114(G04):023

Nabuurs G, Hengeveld G, van der Werf D, Heidema A (2010) European forest carbon balance assessed with inventory based methods – an introduction to a special section. For Ecol Manage 260(3):239–240

Niinistö SM, Silvola J, Kellomäki S (2004) Soil CO_2 efflux in a boreal pine forest under atmospheric CO_2 enrichment and air warming. Glob Change Biol 10:1363–1376

Norby R, Zak D (2011) Ecological lessons from free-air CO_2 enrichment (FACE) experiments. Annu Rev Ecol Evol Syst 42:181–203

O'Neill GA, Hamann A, Wang T (2008) Accounting for population variation improves estimates of the impact of climate change on species' growth and distribution. J Appl Ecol 45:1040–1049

Oliver CD, Larsen BC (1990) Forest stand dynamics. McGraw-Hill Inc., New York

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala S, McGuire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993

Peters GP, Marland G, Le Quéré C, Boden T, Canadell JG, Raupach MR (2011) Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. Nat Clim Change 2:2–4

Petit R, Hu F, Dick C (2008) Forests of the past: a window to future changes. Science 320:1450–1452

Pongratz J, Reick CH, Raddatz T, Caldeira K, Claussen M (2011) Past land use decisions have increased mitigation potential of reforestation. Geophys Res Lett 38:L15,701

Prietzel J, Bachmann S (2012) Changes in soil organic C and N stocks after forest transformation from Norway spruce and Scots pine into Douglas fir, Douglas fir/spruce, or European beech stands at different sites in Southern Germany. For Ecol Manage 269:134–148

Puettmann KJ, Coates KD, Messier C (2009) A critique of silviculture – managing for complexity. Island Press, Washington, D.C

Pyšek P, Krvánek M, Jarosîk V (2009) Planting intensity, residence time, and species traits determine invasion success of alien woody species. Ecology 90:2734–2744

Rahmstorf S, Coumou D (2011) Increase of extreme events in a warming world. Proc Natl Acad Sci U S A 108(44):17,905–17,909

Rehfeldt G, Ying C, Spittlehouse D, Hamilton D (1999) Genetic responses to climate in *Pinus contorta*: niche breadth, climate change, and reforestation. Ecol Monogr 69:375–407

Reick CH, Raddatz T, Pongratz J, Claussen M (2010) Contribution of anthropogenic land cover change emissions to pre-industrial atmospheric CO_2. Tellus B 62(5):329–336

Reif A, Aas G, Essl F (2011) Braucht der Wald in Zeiten der Klimaveränderung neue, nicht heimische Baumarten? – do forests need new, non-native species in times of climate change? Natur und Landschaft 86(6):256–260

Rigling A, Brang P, Bugmann H, Kräuchi N, Wohlgemuth T, Zimmermann N (2008) Klimawandel als Prüfstein für die Waldbewirtschaftung. Schweiz Z For 159:316–325

Rodeghiero M, Heinemeyer A, Schrumpf M, Bellamy P (2009) Determination of soil carbon stocks and changes, chap 4. Cambridge University Press, Cambridge/New York, pp 49–74

Russ W (2011) Mehr Wald in Österreich. BFW-Praxisinformation 24:3–5

Savolainen O, Pyhäjärvi T, Knürr T (2007) Gene flow and local adaptation in trees. Annu Rev Ecol Evol Syst 38:595–619

Schadauer K (1996) Growth trends in Austria. In: Spiecker H, Mielikäinen K, Köhl M, Skovsgaard J (eds) Growth trends in European forests. Springer, Berlin, pp 275–289

Schils R, Kuikman P, Liski J, van Oijen M, Smith P, Webb J, Alm J, Somogyi Z, van den Akker J, Billett M, Emmett B, Evans C, Lindner M, Palosuo T, Bellamy P, Alm J, Jandl R, Hiederer R (2008) Review of existing information on the interrelations between soil and climate change. Alterra, Wageningen. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf

Schindlbacher A, Zechmeister-Boltenstern S, Jandl R (2009) Carbon losses due to soil warming: do autotrophic and heterotrophic soil respiration respond equally? Glob Change Biol 15:901–913

Schindlbacher A, Wunderlich S, Borken W, Kitzler B, Zechmeister-Boltenstern S, Jandl R (2012) Soil respiration under climate change: prolonged summer drought offsets soil warming effects. Glob Change Biol 18(7):2270–2279

Schmidt M, Hanewinkel M, Kändler G, Kublin E, Kohnle U (2010) An inventory-based approach for modeling single-tree storm damage – experiences with the winter storm of 1999 in southwestern Germany. Can J For Res 40:1636–1652

Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. Nature 478:49–56

Schulze E, Schulze I (2010) Sustainable foresting: easier said than done. Science 327:957

Seastedt T (2009) Traits of plant invaders. Nature 459:783–784

Seidl R, Rammer W, Lexer MJ (2011a) Adaptation options to reduce climate change vulnerability of sustainable forest management in the Austrian Alps. Can J For Res 41(4):694–706

Seidl R, Schelhaas MJ, Lexer MJ (2011b) Unraveling the drivers of intensifying forest disturbance regimes in Europe. Glob Change Biol 17(9):2842–2852

Seppälä R, Buck A, Katila P (eds) (2009) Adaptation of forests and people to climate change. a global assessment report, IUFRO World Series, vol 22. IUFRO, Helsinki

Shvidenko A, Barber CV, Persson R (2007) Forest and woodland systems, chap 21. Island Press, Washington, D.C., pp 585–621

Smith WB, Miles PD, Perry CH, Pugh SA (2009) Forest resources of the United States, 2007. General technical report WO-78. U.S. Department of Agriculture, Forest Service, Washington Office

Smith SM, Lowe JA, Bowerman NHA, Gohar LK, Huntingford C, Allen MR (2012) Equivalence of greenhouse-gas emissions for peak temperature limits. Nat Climate Change 2:535–538

Sutton MA, Oenema O, Erisman JW, Leip A, van Grinsven H, Winiwarter W (2011) Too much of a good thing. Nature 472:159–161

Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC (2005) Climate change threats to plant diversity in Europe. Proc Natl Acad Sci U S A 102(23):8245–8250

Tollefson J (2012) Brazil set to cut forest protection. Nature 485:19

Tomiczek C, Hoyer-Tomiczek U (2007) Der Asiatische Laubholzbockkäfer (*Anoplophora glabripennis*) und der Citrusbockkäfer (*Anoplophora chinensis*) in Europa – ein Situationsbericht. Forstschutz Aktuell 38:2–5

Tomppo E, Gschwantner T, Lawrence M, McRoberts RE (eds) (2010) National forest inventories – pathways for common reporting. Springer, Heidelberg

Ulbrich U, Leckebusch GC, Pinto JG (2009) Extra-tropical cyclones in the present and future climate: a review. Theor Appl Clim 96:117–131

Van Miegroet H, Olsson M (2011) Ecosystem disturbance and soil organic carbon – a review, chap 5. Wiley-Blackwell, Chichester, UK, pp 85–117

van Oijen M, Jandl R (2004) Nitrogen fluxes in two Norway spruce stands in Austria: an analysis by means of process-based modelling. Aust J For Res 121:167–182

Vesterdal L, Leifeld J, Poeplau C, Don A, van Wesemael B (2011) Land-use change effects on soil carbon stocks in temperate regions – development of carbon response functions, chap 3. Wiley-Blackwell, Chichester, UK, pp 33–48

Vuichard N, Ciais P, Belelli L, Smith P, Valentini R (2008) Carbon sequestration due to the abandonment of agriculture in the former USSR since 1990. Glob Biogeochem Cycle 22:GB4018

Wang T, Hamann A, Yanchuk Y, O'Neill G, Aiken S (2006) Use of response functions in selecting lodgepole pine populations for future climates. Glob Change Biol 12:2404–2416

Wang G, Innes J, Lei J, Dai S, Wu S (2007) China's forestry reforms. Science 318:1556–1557

Weiskittel AR, Hann DW, Kershaw JA Jr, Vanclay JK (2011) Forest growth and yield modeling. Wiley, Chichester

Wermelinger B (2004) Ecology and management of the spruce bark beetle *Ips typographus* – a review of recent research. For Ecol Manage 202:67–82

Zhou G, Liu S, Li Z, Zhang D, Tang X, Zhou C, Yan J, Mo J (2006) Old-growth forests can accumulate carbon in soils. Science 314:1417

Zianis D, Mukkonen P, Mäkipää R, Mencuccini M (2005) Biomass and stem volume equations for tree species in Europe. Silva Fenn Monogr 4:63

Zimmermann NE, Yoccoz NG, Edwards TC Jr, Meier ES, Thuiller W, Guisan A, Schmatz DR, Pearman PB (2009) Climatic extremes improve predictions of spatial patterns of tree species. Proc Natl Acad Sci U S A 106:19,723–19,728