Climate change
Forest
Forestry
RELATIONSHIPS

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Contents

1. Introduction

1.1. Climate change has become a fact. The question concerns the pace and nature of this change, as well as the decisions and measures to be taken in order to limit its effect on humans and the economy. The interrelationships between climate, forest and economic activity, based on wild nature's biological production, are equally apparent, though not always sufficiently recognized, as they are multi-faceted and sometimes go in opposite directions. It is impossible to exhaust, in a synthetic study like this, this complex, interdisciplinary subject undergoing continuous development. Therefore, the focus should be on the most important, selected issues and the Polish forest economy share in addressing them.

The mechanisms of carbon absorption and emission are at the core of the mutual relationships between forest, forestry and climate change whose causes are looked for in the growing concentrations of greenhouse gases, like CO_2, in the atmosphere. Let us not forget that life on our planet is made up of carbon compounds. Carbon cycling in the biosphere has shaped and will continue to shape carbon resources in the atmosphere, in the living and dead organic matter (biomass) and in fossil deposits. In each case, the binding of carbon dioxide with water and solar energy in the process of photosynthesis of autotrophic plants is the primary process initiating its absorption, accumulation and emission. All the rest of the world feeds only on what is produced by plants absorbing carbon from the atmosphere. Organic matter not only accumulates, but also releases carbon in the (oxidation/respiration) processes. The processes shaping natural environment, nature as a whole and the living conditions, including humans', are involved in and accompany biomass production.

It is through the production of biomass that forests have shaped and continue to shape climate and air composition, regulate precipitation, temperature and air movements, create conditions necessary for the existence of a huge number of plant and animal species, accumulate gene resources and organisms being biomass producers and consumers, as well as those restoring biomass to its original usefulness state in the ecological energy-matter transformation processes. Climate changes affect nature's functioning with all these phenomena and processes. Some have a damaging effect on them, others favours them, either instantly or in the near or far perspective of the evolution process.

Forests participate in these transformations more than other nature's structures. Covering about 30 per cent of landmass, they are the most important terrestial carbon absorbers. Therefore, their protection, management method, reduction or increase of forest area, improvement or degradation of their condition are the principal issues related to the preservation of the global climate equilibrium.

1.2. Forests occur in a quadruple role in the climate change process, and these roles set the directions of mutual impact of climate, forest and the economy:

1) as "the cause", that is as a source of greenhouse gases (GHGs), mainly CO_2, but also methane, due to the growth of emissions as a result of deforestations (change of land use forms), incorrect forest uses (intensive soil cultivation, lack of regenerations or late regenerations, forest fires or retaining standing trees until stand disintegration);
2) as "the victim" of climate change causing increased vulnerability to pests and deceases, increased forest flammability, changes in species composition, changes in the natural ranges of tree species;
3) as "the beneficiary" of climate changes, benefiting from the "greenhouse effect" and the "fertilization effect"(eutrophicating

compound deposit) stimulating biomass growth, which is manifested in growth of standing stock, increment growth rate, and beneficial conditions for growth and regeneration;

4) as “the remedy” for global changes and the poor condition of the environment on account of: a) forest’s ability to absorb and relatively permanently accumulate carbon in forest ecosystems’ structures (wood, soil), b) wood’s substitutive properties for materials whose production damages the environment and contributes to climate change (construction materials, such as steel, aluminium, cement, brick, plastic – packages), c) wood’s substitutive properties for fossil fuels, d) ability to regenerate to the benefit of the environment;

Therefore, the role of forests and forest management depends on the methods and targets of forest economy and the ways by which their produce, particularly wood, is used. The above mentioned roles which forests can play in climate shaping, and the ensuing forest management’s impacting possibilities, reveal a significant lack of knowledge. It is particularly so, because the extent of response of large nature’s systems to the environmental conditions existing before the change was unknown, the knowledge of the structure and functions of forest ecosystems was only fragmentary and the object of study changed throughout the research process. There may appear a situation where practical actions will be largely based on the results of extrapolation of historical knowledge, rather than parameterized for the new conditions, with forecasting possibilities being simultaneously limited.

1.3. The Framework Convention on Climate Change (UN FCCC 1992) and the Kyoto Protocol set by the Parties to the Convention (1997) point to forests as one of the most effective terrestrial absorbers of atmospheric carbon. The simplest method of forestry’s participation in CO_2 reduction and climate change mitigation is augmentation of forest cover, that is the area of carbon absorption and biomass production. Other forms of land use like agriculture, industrial and transport infrastructure, urbanization or new settlements, where emission surpasses absorption, are certainly a constraint here.

Wood is the main element of forest biomass used by man on which forest management may have the greatest impact and shape it to its purpose in terms of quantity and quality. The essence of climate protection in this case consists in retaining carbon assimilated in wood longer than its production cycle (e.g. rotation). Thus, the concentration of CO_2 in the atmosphere and greenhouse effect are effectively reduced, slowing down climate changes.

An equally positive effect can be achieved using wood in substitution for fossil fuels (the largest source of carbon emissions to the atmosphere) or materials whose production is energy-consuming or based on “dirty” technologies (steel, concrete, plastic).

In addition to wood, also forest soil is the place of a relatively steady carbon accumulation. However, forest management’s impacting possibilities are here strongly limited by habitat quality and soil capacity.

All the above gives forests and forestry a historical chance to play a key role in managing the Earth’s natural, terrestrial resources and alleviating climate change. This can be accomplished through:

- forest cover growth and land use rationalization,
- forest management based on the sustainable development principle (species composition regulation, stand conversion, rationalization of tending cuts, augmentation and protection of organic matter in soil, etc.),
- rationalization of timber use, increase of its durability and utilization of its substitutive properties (construction timber, fuel timber, other).

It is estimated that the above actions may contribute to a global reduction of the pace of climate change by about one fifth.

Forest management was for the first time referred to as a tool mitigating climate changes already in the 1970s (DYSON 1977). However, it was not until the Kyoto Protocol that such a possibility was considered at global level.

The Kyoto Protocol is in fact the first global “environmental” tool regulating the world economy. In a move to protect the planet’s sustainability, it deals with the mechanisms governing development, setting technological barriers to energy consumption, regulating its forms and sources. The careful approach of some states to the reduction of greenhouse emissions (as this means reduced economic growth and increased unemployment, e.g. in the USA) is accompanied by a distrust of other states feeling that their sovereignty in the use of their own natural resources is limited (limitation of deforestations in the poor countries of the South by the rich countries of the North). The greatest controversies concern the methods of involving forest and forestry in the fulfilment of their obligations and in making use of absorption in the emission balance.

2. The role of forests in the global carbon resources

2.1. The main global carbon pools and annual flows between them are illustrated in the following drawing:

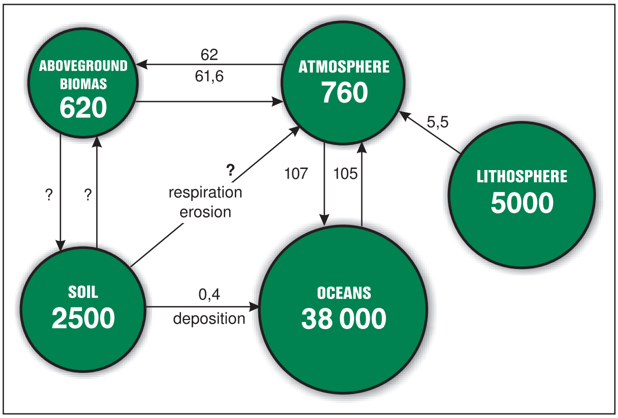


Fig. 1. The main global carbon pools and annual flows between them (in Pg), (according to LAL, 1999)

The Earth's biologically active area plays the principal role in the accumulation and cycling of carbon in the biosphere. Approximately 125 gigatons (Gt)[1] of carbon is exchanged between vegetation, soil and the atmosphere, or two fifth of the total carbon exchange between the earth and the atmosphere; forests which globally accumulate more than half of the planet's carbon participate in about 80% of this exchange (Fig. 2).

Carbon exchange means not only its absorption, also its release. The

[1] One Gt equals to one billion tons.

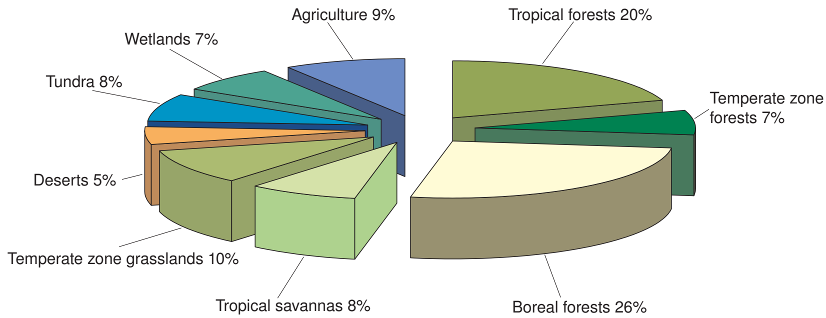


Fig. 2. Carbon distribution by terrestrial ecosystem (DIXON et al. 1994)

main source of carbon emissions is, apart from fossil fuel combustion, forest felling. There is evidence that deforestation in the 1980s is responsible for about one fourth of all anthropogenic carbon emissions to the atmosphere (HOUGHTON 1999). Nevertheless, there are sufficient conditions for the biosphere to absorb or accumulate during the next 50 years 60 to 87 Gt of carbon in forest resources, and 23 to 44 Gt of carbon in agricultural soils (BROWN *et a*l. 1996).

Information on the size of carbon pools accumulated in forest ecosystems is divergent and cannot be compared due to different measurement techniques which change over time and space as a result of geographic-climate differences (also microclimate differences) and forest development phases (OLLINGER, SMITH 2005; BERT, DANJON 2006; OSTROWSKA 1999, 2006; LAMERS et al. 2006; LAL 2005; BERGH et al. 1999). The main “reservoirs”, where carbon is accumulated and stored in forest ecosystems, and the average share of carbon pools in the global balance can be presented as follows (RYKOWSKI 2006 on the basis of literature):

- assimilatory apparatus (crown) – approx. 7.0% C;
- stem/trunk– about 19.0% C (the trunk contains approx. 66.0% of whole tree biomass, of which 58.0% is in wood and 8.0% is in bark);

- stumps and roots– approx. 7.0% C (about 14.0% of wood biomass);
- wood residues (twigs, slash) – approx. 5% C;
- litter – approx. 11% C;
- organic matter in soil – approx. 46% C;
- shrub layer – approx. 5% C.

In general, forests contain more than half of the carbon deposited in terrestrial vegetation and soil, estimated at approximately 1200 Gt. Boreal forests accumulate much more carbon than any other terrestrial ecosystems (26% of all terrestrial carbon resources),while tropical and temperate zone forests – 20% and 7%, respectively (DIXON *et al*. 1994), (Fig. 2).

2.2. Soil is one of the most important carbon pools in forest ecosystems featuring high accumulation permanence, yet arousing much controversy and doubt as to its quantity and sequestration mechanisms. As a result of the humification process, consisting of a number of complicated, enzymatic hydrolysis, oxidation and polymerization processes, organic carbon transforms into dark-coloured, cyclic, colloidal compounds, called humus substances. These substances are very resistant to decomposition and therefore they bind carbon in a very permanent way causing soil to become a CO_2 absorber. This applies first of all to that part of the humus which enters into reaction with the mineral fraction of soil, particularly with clay minerals (RICHARDSON, EDMONDS 1987; THENG *et al*. 1989).

It is estimated that global resources of carbon compounds in soil are nearly 2.5 times larger than in the atmosphere and nearly 4.5 times larger than in the aboveground biomass of terrestrial ecosystems. A detailed assessment of the possibility of permanent carbon sequestration by forest soils is very difficult. Also, a precise measurement of organic carbon resources in soils is hindered due to a great variety of chemical compounds containing this element, as well as due to the temporal and spatial variability of soils (STEVENS *et al*. 2006). At the same time, these data are urgently needed for reliable reporting on Convention implementation and for building a strategy to reduce of emissions of greenhouse gases as well as models and forecasts of carbon accumulation in forests.

In forest soils, organic carbon can be accumulated even down to a considerable depth; at a level of 20 to 80 cm below ground, there still is 40 to 50 % of the total carbon pool. This fact should be taken into consideration while estimating carbon deposits in forest soils.

Habitat features characterizing a habitat-type of forest have a large impact on carbon accumulation in raw humus and endohumus.

It should be emphasized that organic carbon resources in mineral soil layers undergo high fluctuations over time and space. In the case of homogenous, tropical forests, the total carbon resource may differ by 600%, oscillating between 50 and 300 tones per hectare (SOMBROEK *et al*. 1999). In the temperate zone, differences in carbon deposits are of course much bigger due to a high heterogeneity of forest soils.

Therefore, the carbon deposited in forest ecosystems' soil and litter constitutes a considerable part of its whole resource. On a global scale, the amount of carbon in soil accounts for more than half of the carbon resources in forests. There are however differences depending on

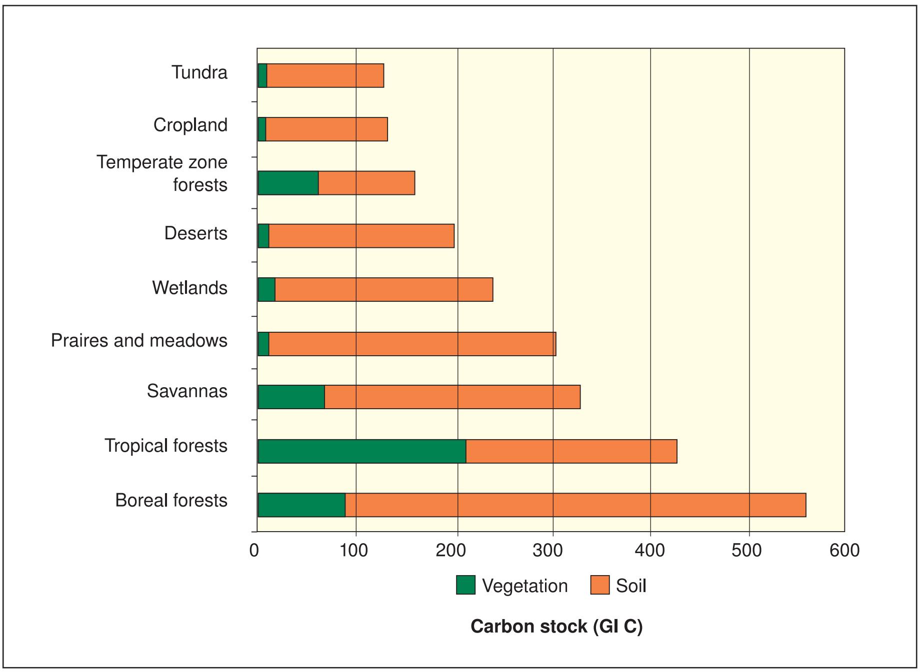


Fig. 3. Carbon stock above ground level and in soil by vegetation formation type (according to IPCC LULUCF 2000)

climate zone. About 80–90% of carbon in boreal ecosystems is accumulated in the form of organic matter in soil, while in tropical forests, carbon is evenly split between soil and vegetation (Fig. 3).

The main cause of this difference is the impact of temperature on the production and decomposition of organic matter. In the boreal forest zone, organic matter accumulates in soil as its decomposition pace is slower than its growth pace as a result of production. In the sub-tropical zone, higher temperatures initiate a fast organic matter decomposition process and its fast cycling in the form of nutrients.

3. Carbon emissions from forest ecosystems

Until the 19th century, people had had a small impact on terrestrial carbon resources, however since the industrial revolution, man has marked its activity in global carbon cycling by using fossil fuels and cutting forests.

Due to land use changes between 1850 and 1980, over 100 Gt of carbon was emitted to the atmosphere which accounted for one third of the total amount of carbon emitted by people over that period (HOUGHTON 1996).

The 19th century saw the highest degradation of forests in the temperate climate zone (North America, Europe). In the 20th century, the area of temperate climate forests stabilized, and the tropical primeval forests became the main source of carbon emissions (HOUGHTON 1996), (Fig. 4). Today, forest area in the developed countries slightly increases; between 1980 and 1995, its average growth amounted to 1.3 million hectares per year (FAO 1999). In recent years, many forests in the temperate climate zone (e.g. in Europe and east of North America) have become carbon reservoirs as a result of established plantations and afforestation of the abandoned agricultural land, while tropical forests have become the main area emitting carbon. The rate of cutting tropical forests between 1980 and 1995 was estimated at 15.5 million hectares per annum (FAO 1999).

The net emission of carbon resulting from land use in the 1980s is estimated at about 2–2.4 Gt per annum (Fig. 4), or nearly 23–27% of

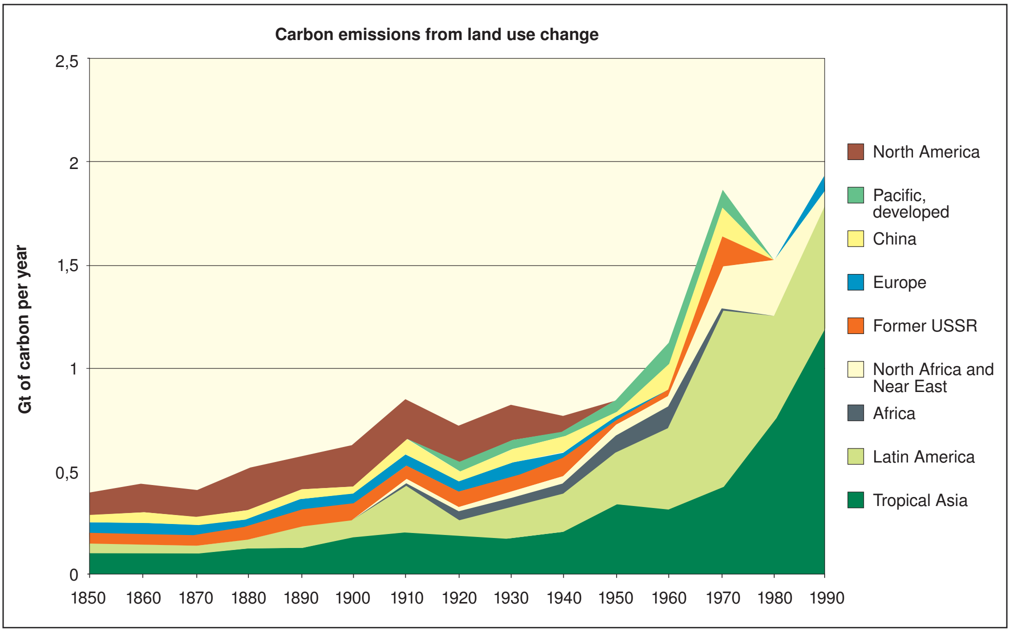


Fig. 4. Carbon emissions related to land use change in different parts of the world

total CO_2 emissions caused by humans (HOUGHTON 1999). The largest impact on the emission of carbon to the atmosphere due to land use change is from the conversion of tropical forests to other forms of use (*slash & burn*), including forest cutting, burning, and crop farming or livestock breeding. Biomass burning also releases other greenhouse gases to the atmosphere, like methane and nitrogen oxides. Burning forest biomass gives 10% of the global emission of methane. Forest degradation is also reflected in carbon losses. It is estimated that in the 1980s, the annual net emission of carbon stood at 0.6 Gt (HOUGHTON 1996). In the tropical part of Asia, carbon losses caused by forest degradation nearly equal the losses caused by deforestation.

There are proofs that changes in the concentration of atmospheric gases caused by human activity affect the carbon cycle in forests. Global concentration of atmospheric CO_2 increased from 280 ppm before the industrial revolution to 370 ppm in 2000; also deposition of nitrogen compounds increased. Both phenomena lead to a so called “fertilization effect”, or plant productivity growth.

Recent years have seen a significant biomass growth on permanent observation plots established in the old-growth, natural forests of North and South America. Other proofs of increased carbon assimilation in forestland come from micrometeorological measurements of the CO_2 flowing across the primeval forest, as well as estimations of atmospheric CO_2 distributions at the continents scale. Also findings of European studies indicate growth of growing stock and increment rate in the temperate climate forests (SPIECKER *et a*l. 1996; KARJALAINEN *et al*. 1999). It means that through a combined effect of afforestation, regeneration and rehabilitation of degraded forests, as well as support of the existing forests' growth, carbon absorption by those forests is approx. 1–3 Gt per annum (MALHI, BALDOCCHI and JARVIS 1999).

4. Climate change versus forest occurrence and structure

If temperature on the Earth's surface increases during the 21st century, as forecasted, all ecosystems will experience the most violent and fastest changes since the glacial era. Forest distribution on our planet and its composition will undergo deep changes, and the forest administration and management strategies will have to adapt to the new situation. The scenarios for the 21st century developed by the IPCC XXI are usually unanimous as concerns global warming, but less unanimous as concerns the level of precipitation (the "dry" variant and the "wet" variant is foreseen). The most essential changes predicted for the end of the 21st century can be summarized as follows:

- concentration of atmospheric CO_2 is likely to double,
- mean temperature will rise by approx. 1.5–4.5^{o}C,
- precipitation will increase globally by approx. 3–5%,
- sea level will rise by 45 cm.

As global forecasts are not very precise, and frequently contradictory, in-depth analyses are needed for making strategic, let alone operating decisions at different organization levels, as well as temporal and spatial scales. It is expected that climate change altering the recent system of temperatures, humidity, precipitations, etc. will be accompanied first of all by changes in vegetation occurrence. The hypothesis is confirmed by paleobotanical and ecophysiological studies, as well as the wide-ranging observations of ecosystems and computer simulations.

Climate changes over the past 10,000 years resemble those which are anticipated should the atmospheric CO_2 concentrations double. The contemporary Quaternary Period can be divided into the Holocene (approx. 10 thousand years) and Pleistocene (approx. 10 thousand to nearly 2 million years back). The Holocene followed the periods of Pleistocene glaciations, after the Glacial Epoch; this is the climate warming period which has lasted till the present. During that time, mean temperature has increased by approx. $2^{O}C$. This temperature is also shown in the GCMs model explaining the circulation of greenhouse

gases (SHUGART *et al.* 2003). The Holocene decided about the structure of contemporary forests by shaping the current ranges of occurrence of plant species, including forest trees.

Paleobotanical studies have shown a natural northward shift of tree species ranges in North America by some hundred kilometres (DAVIS 1981; WEBB 1988). This concerns species such as pine (*Pinus strobus*), oak (*Quercus* spp.), maple (*Acer* spp.), spruce (*Picea* spp.). Those shifts have turned to be significant only at certain locations, e.g. the Eastern Coast of North America. A characteristic feature of these changes is the retreat of all studied species northwards.

5. Probable changes in the ranges of main forest tree species in Europe

The results of model simulations show dramatic changes in the occurrence ranges of contemporary forest-forming tree species in Europe, at the assumption that atmospheric CO_2 concentrations will double (SYKES, PRENTICE 1995). It is of special significance for Poland where the majority of analyzed species are nature-valuable and economically valid forest-forming species whose natural ranges cross Poland's territory (Fig. 5).

The anticipated changes concern the main forest-forming species which lose their recent ecological optima and will be exposed to all ensuing consequences, starting from biochemical and physiological changes which reveal themselves first in phenology and then in productivity, and which will have an impact on their health condition, susceptibility to known and unknown biotic threats, as well as resistance to abiotic environment factors. It is difficult to predict now all possible consequences to forest management and forest status, particularly so, because changes will not confine to species level only, but will also affect the ecosystem and landscape.

Potential forest ecosystem responses to climate change can be grouped as follows:

- changes in forest location,
- changes in forest structure,
- changes in forest productivity.

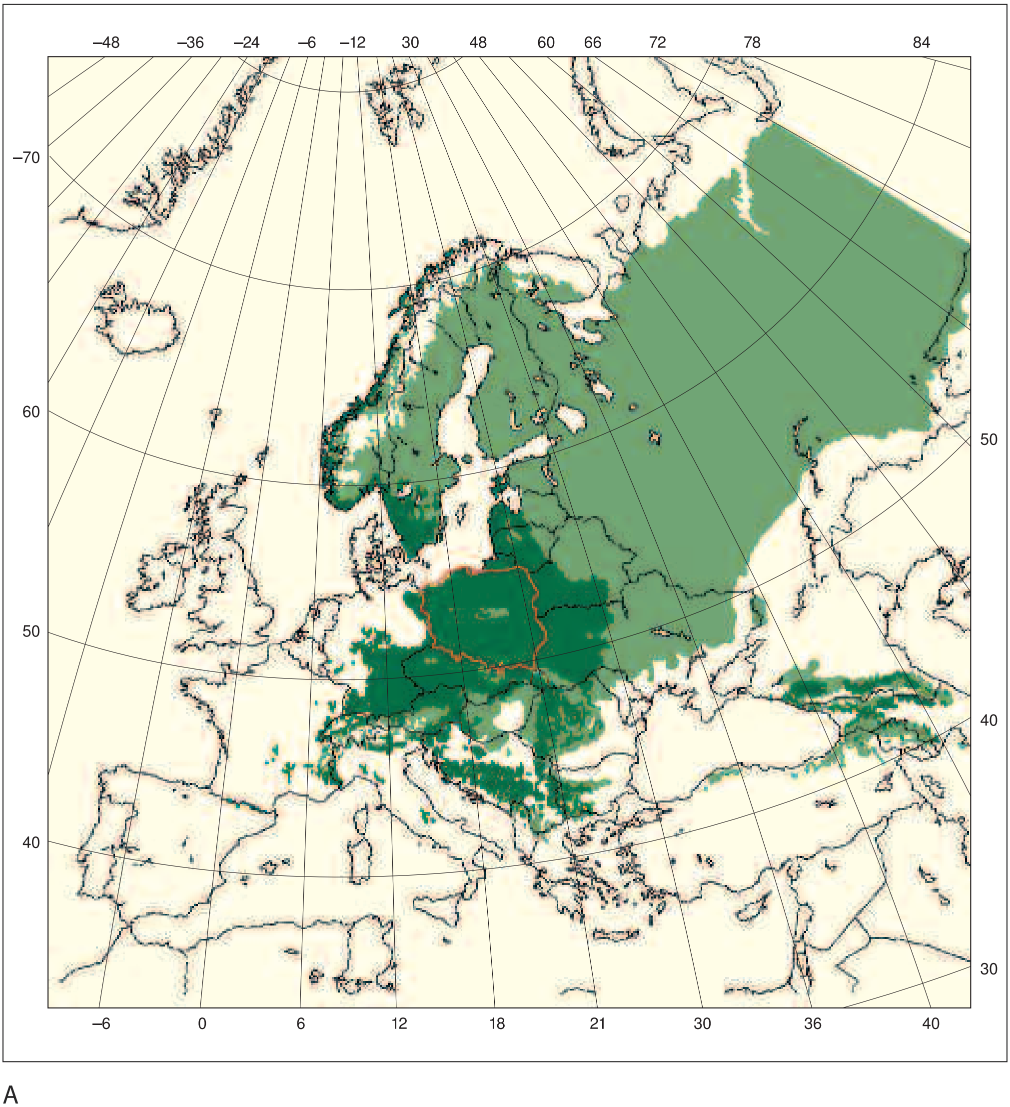
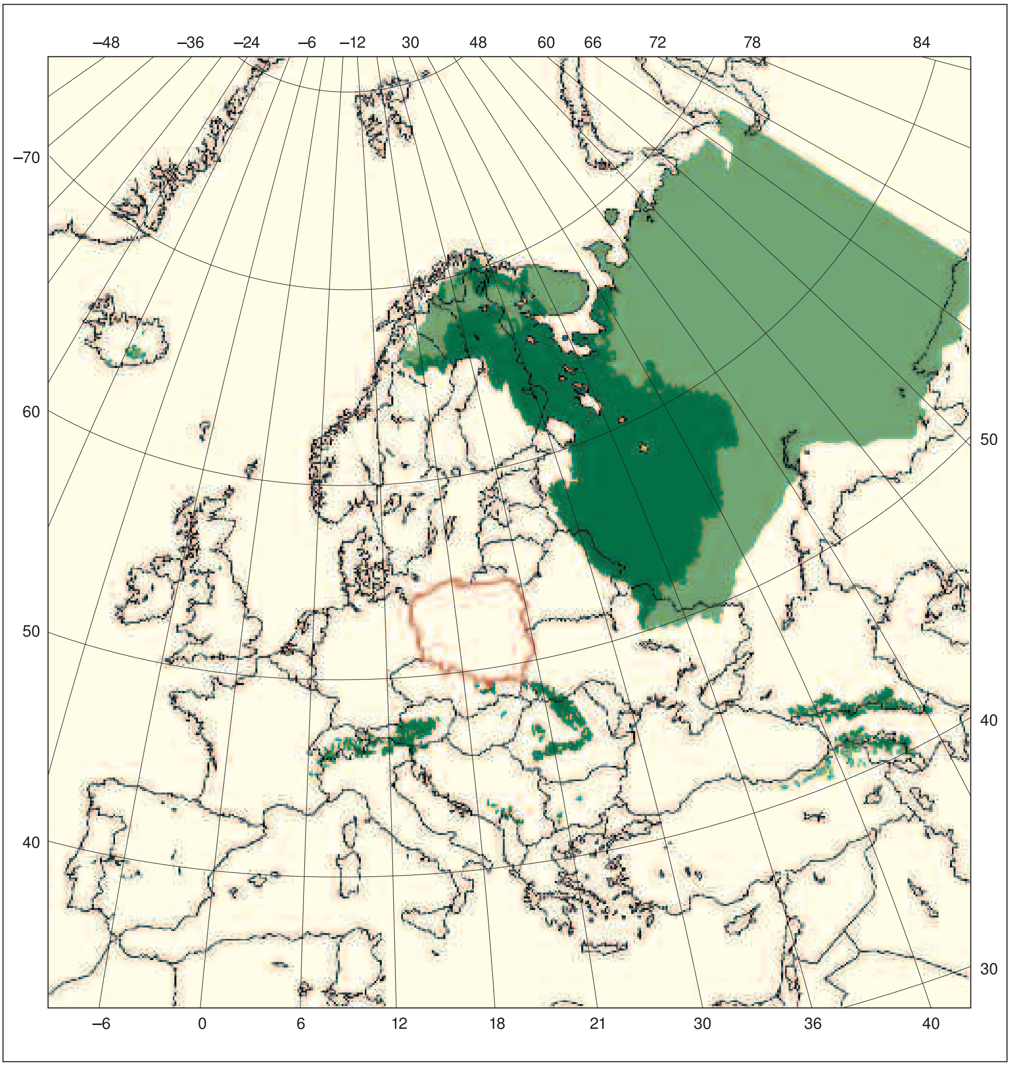


Fig. 5. Changes in the natural occurrence ranges of Scots pine (*Pinus sylvestris*) in Europe.
A – current status, B – climate 2×CO_2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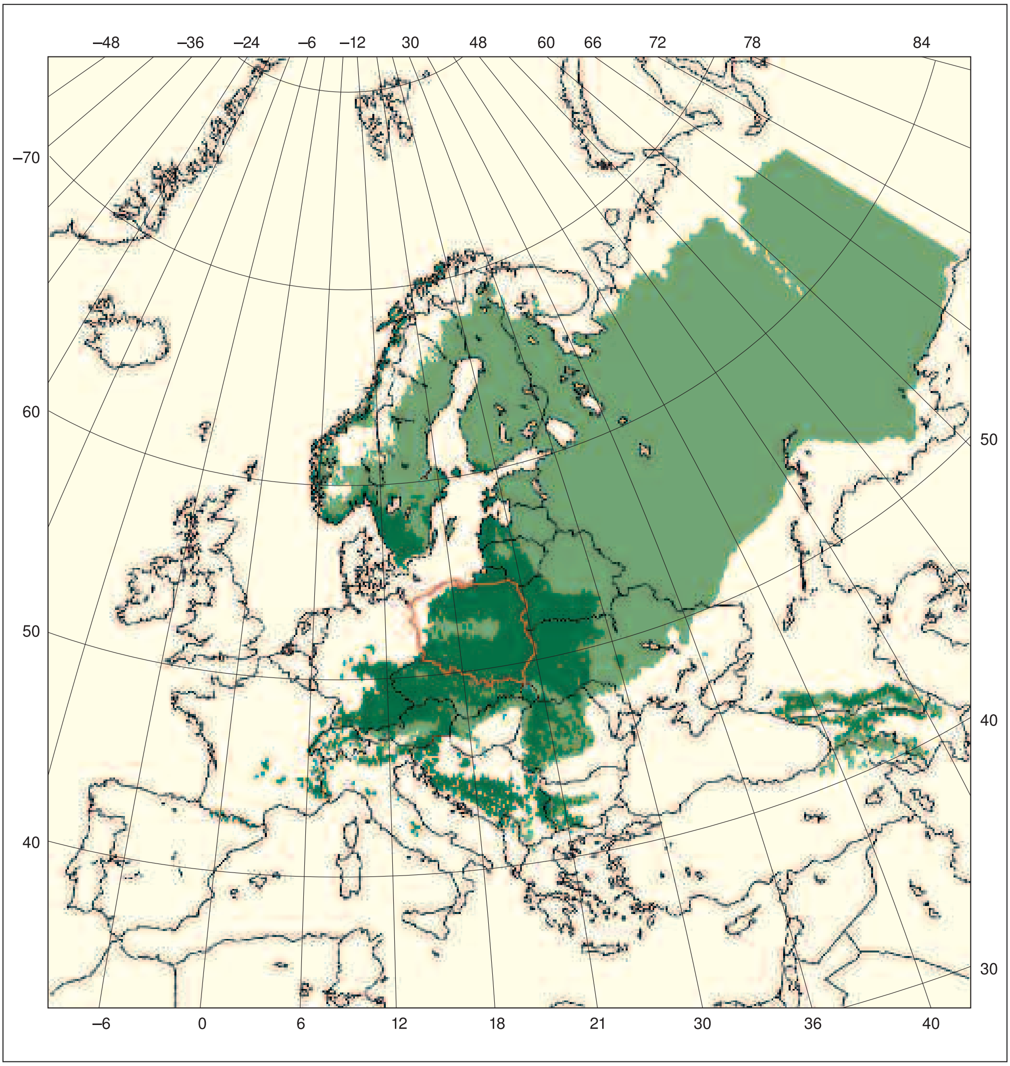

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Fig. 5. Cont'd. Changes in the natural occurrence ranges of Norway spruce (*Picea abies*) in Europe.
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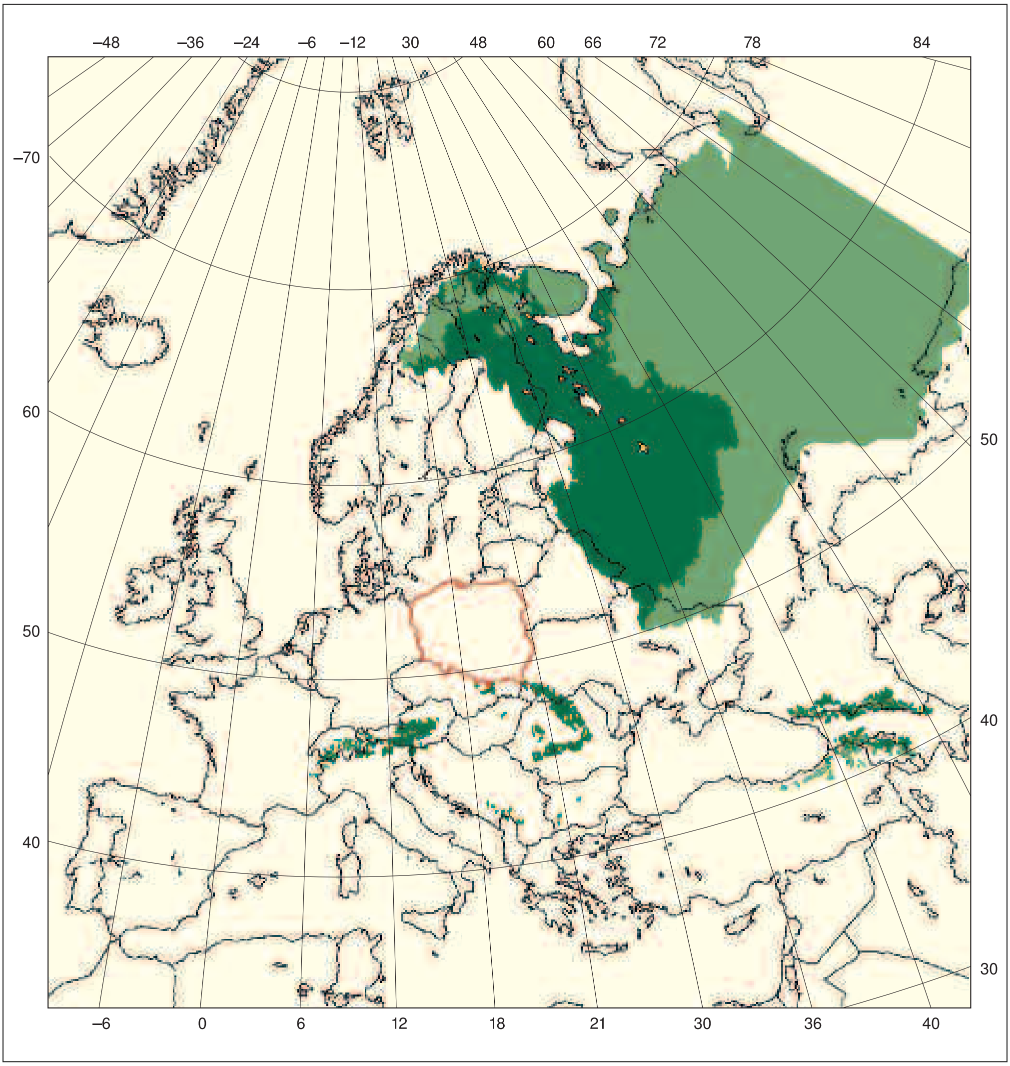
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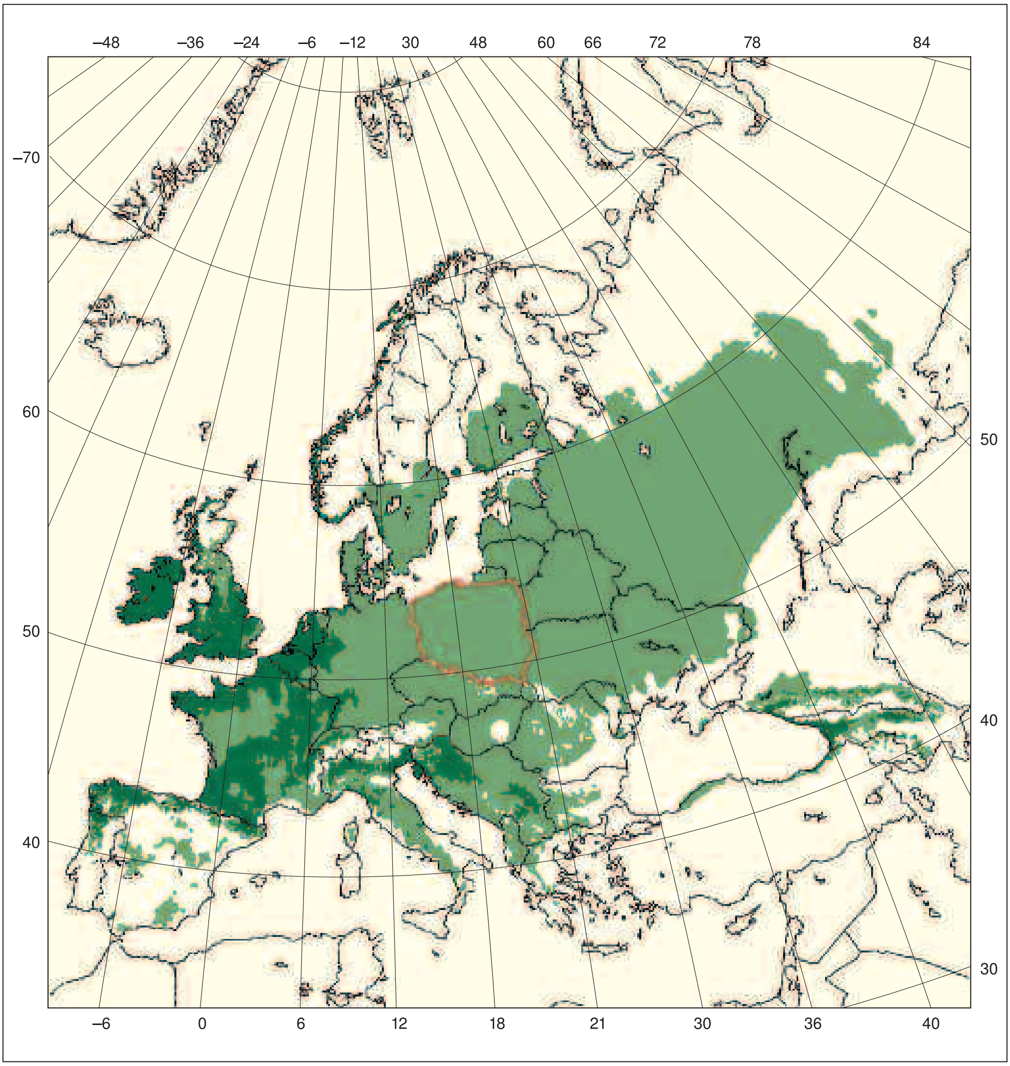

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Fig. 5. Cont'd. Changes in the natural occurrence ranges of pedunculate oak (*Quercus robur*) in Europe.
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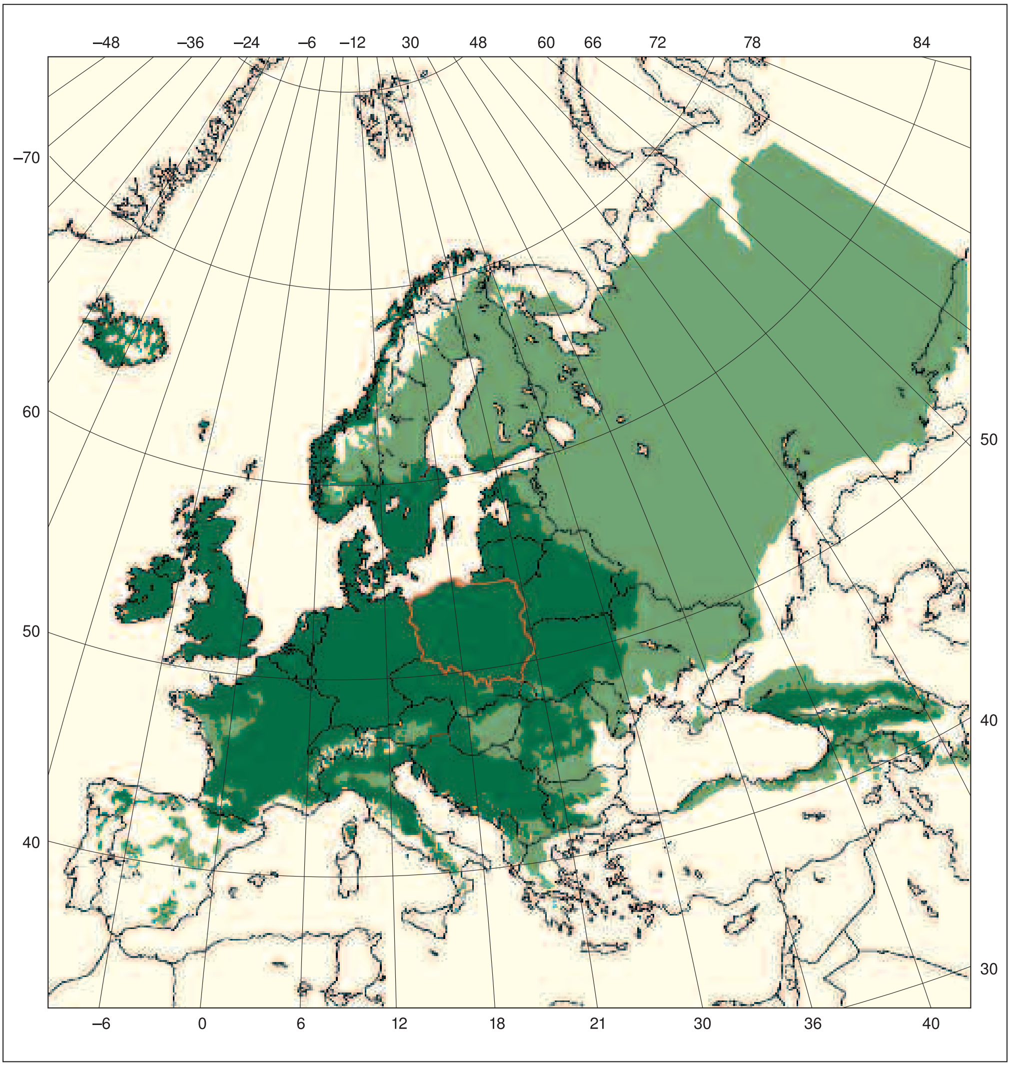
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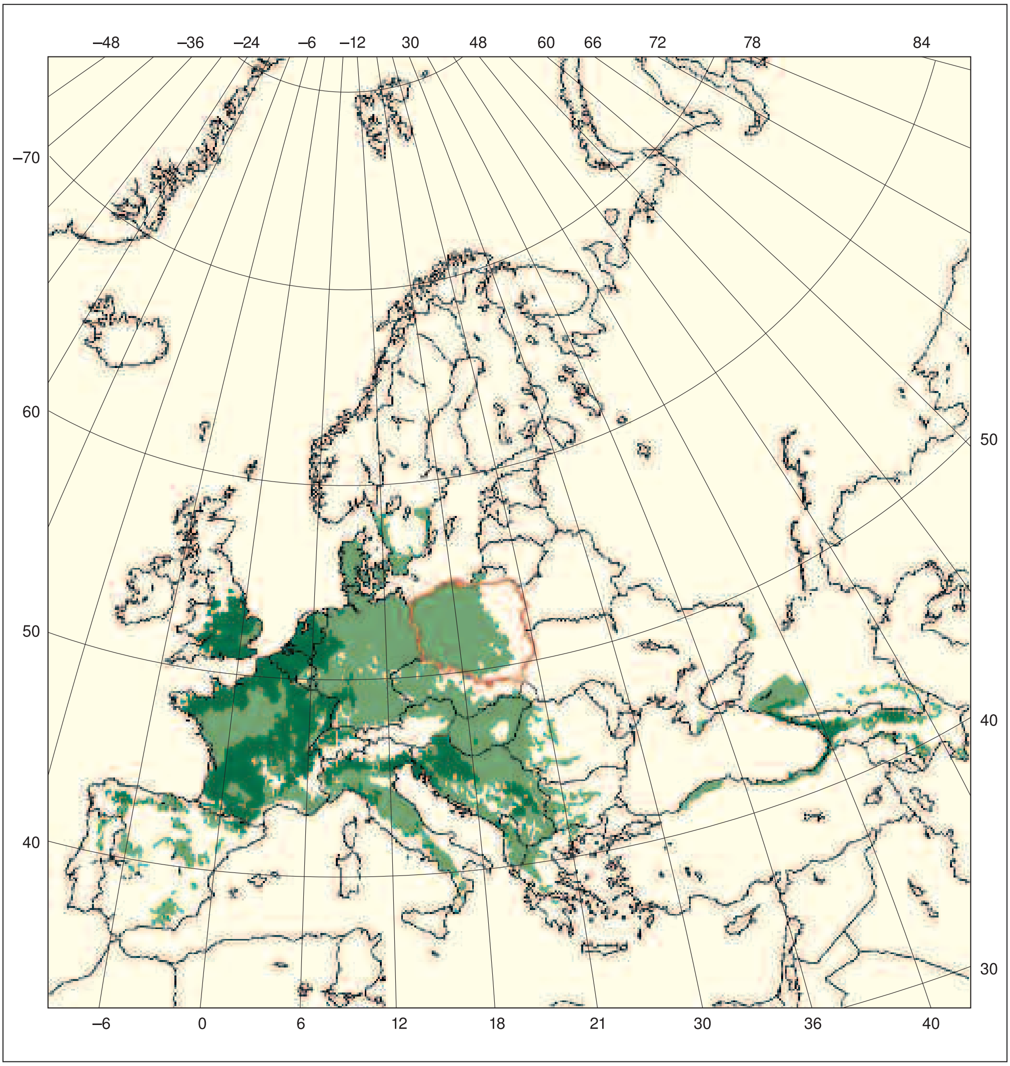

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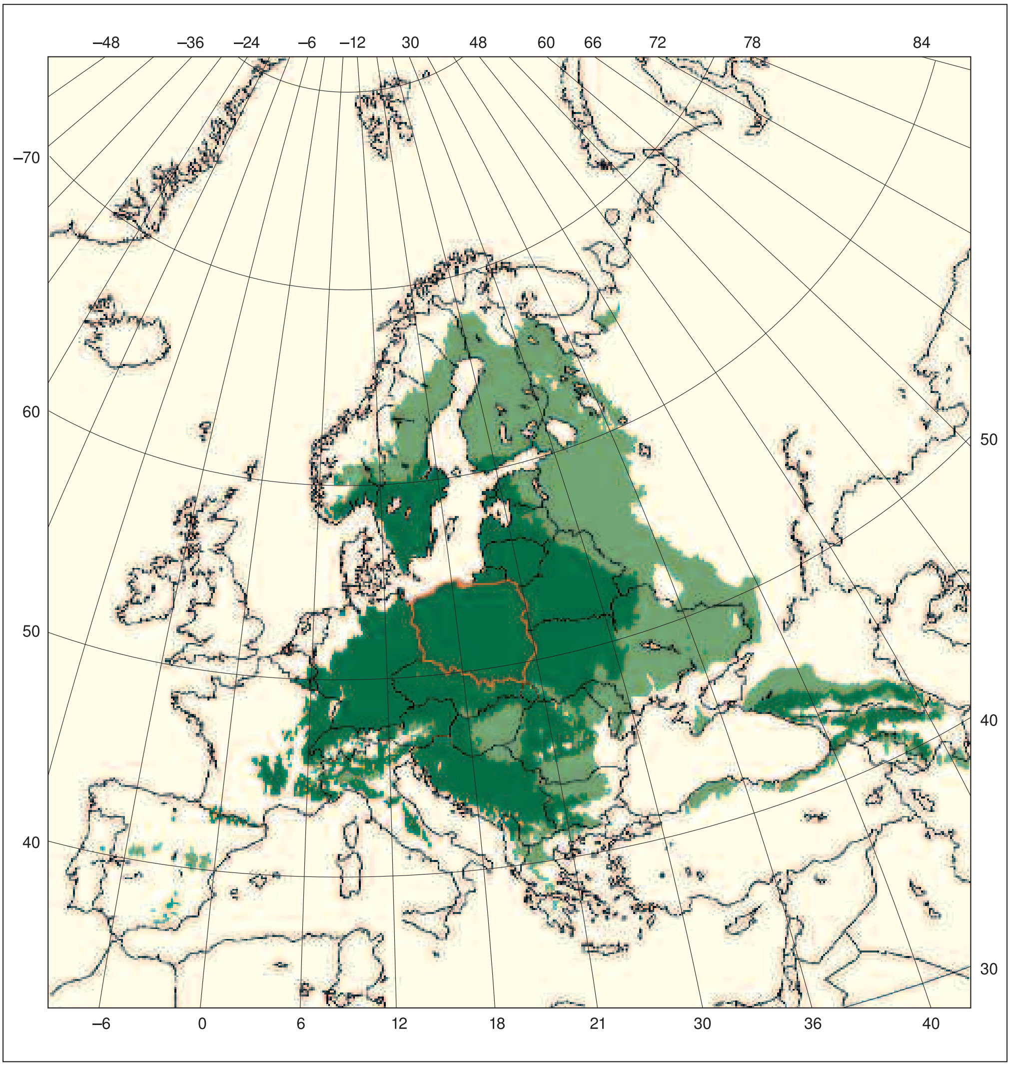
Fig. 5. Cont'd. Changes in the natural occurrence ranges of European beech (*Fagus sylvatica*) in Europe. A – current status, B – climate 2×CO_2



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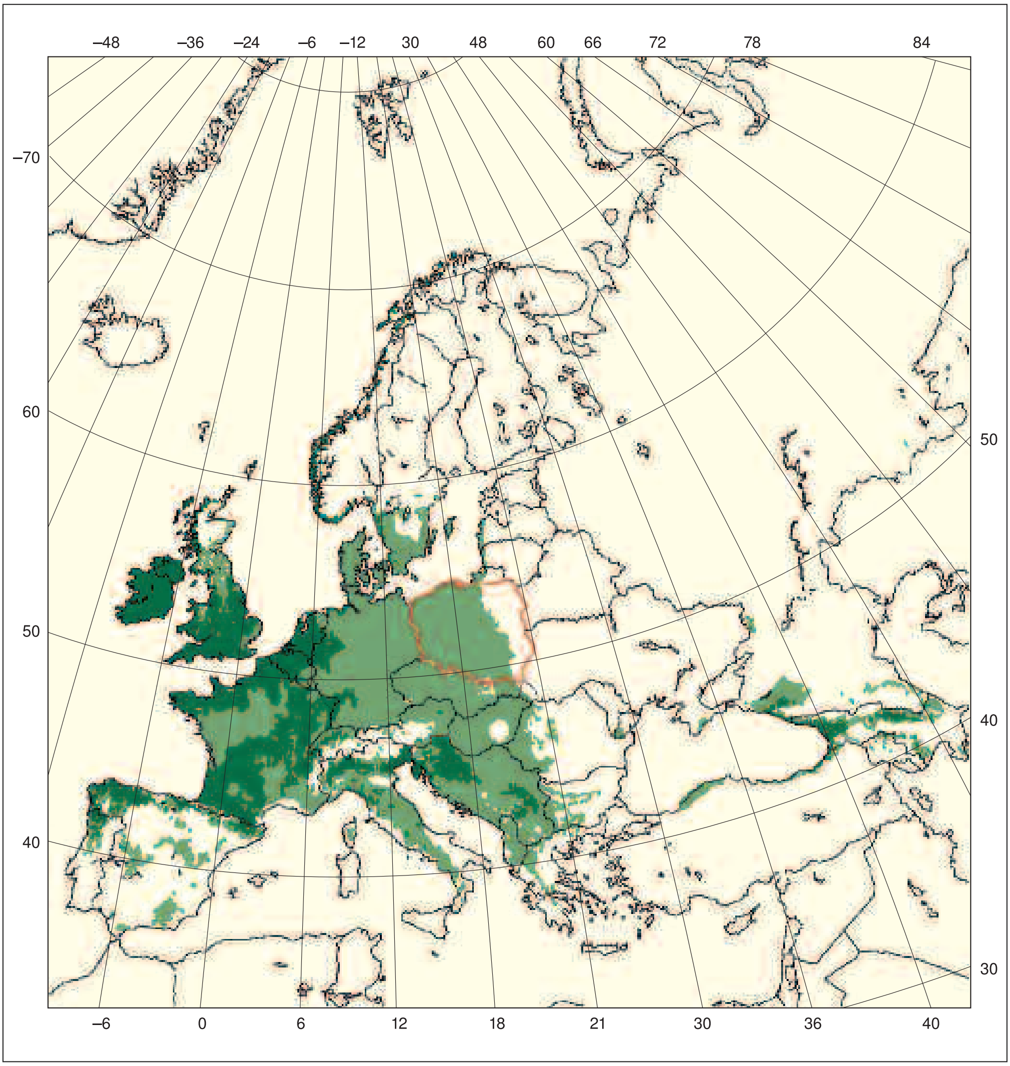

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Fig. 5. Cont'd. Changes in the natural occurrence ranges of sessile oak (*Quercus petraea*) in Europe.
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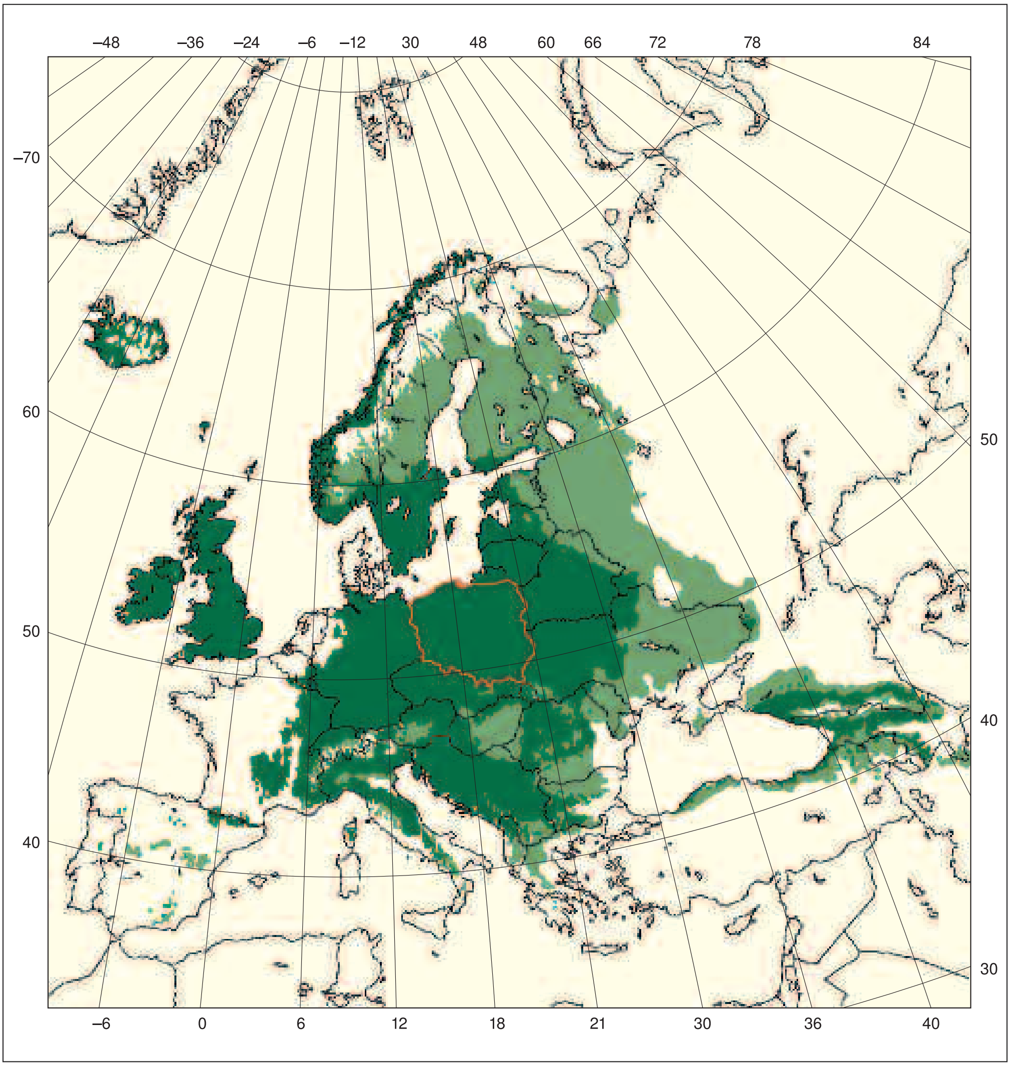
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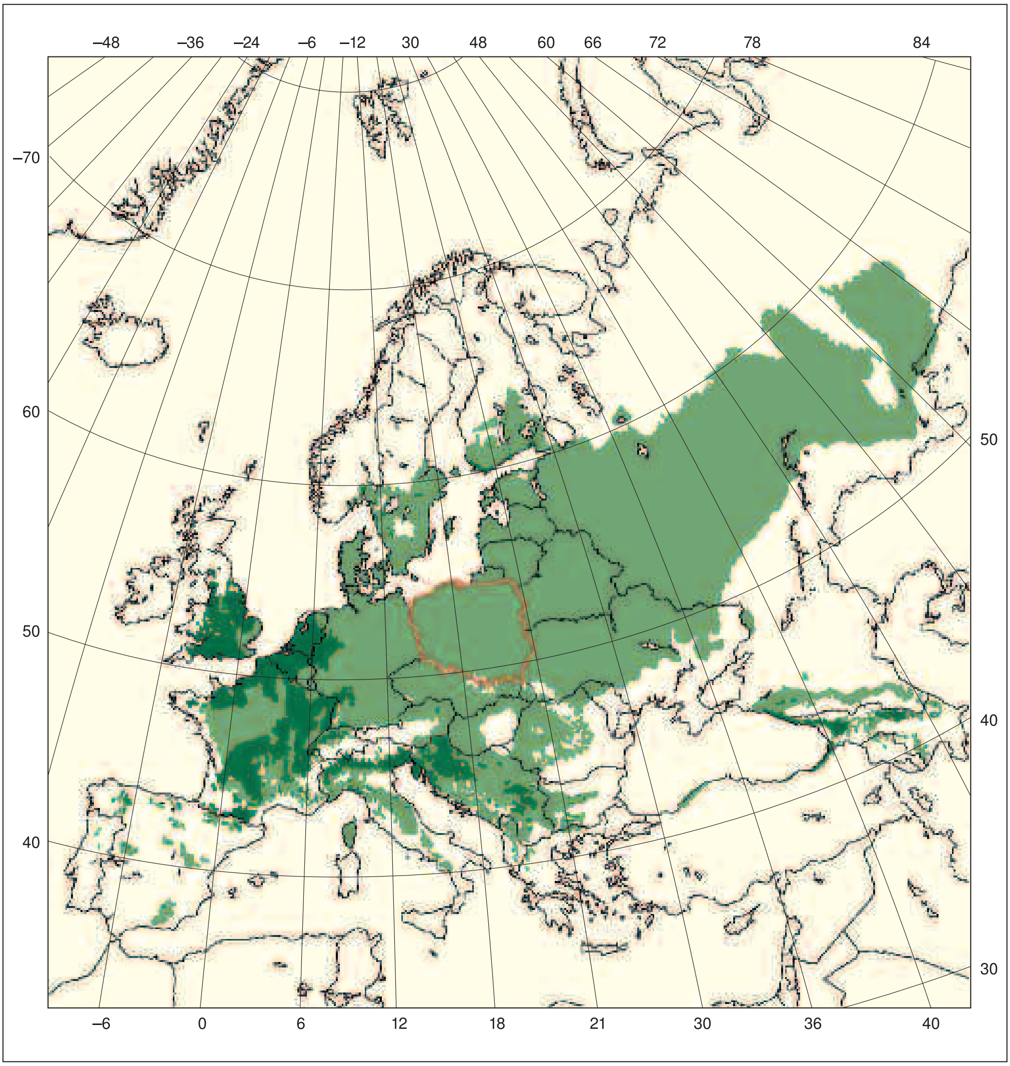

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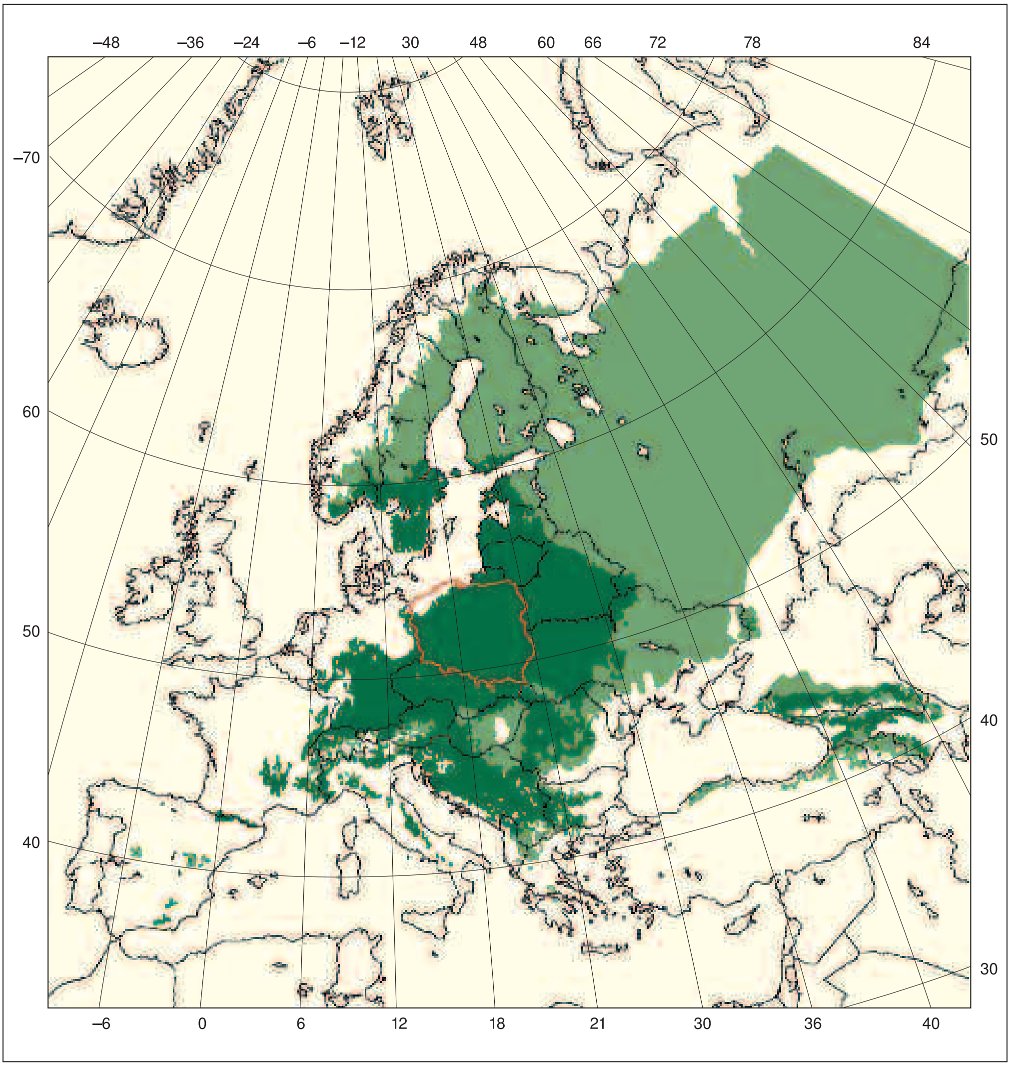
Fig. 5. Cont'd. Changes in the natural occurrence ranges of small-leaved lime (*Tilia cordata*) in Europe.
A – current status, B – climate 2×CO_2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Understanding the impact of climate change on forest ecosystems requires knowledge of the ways of forest's functioning in different biological and ecological, as well as spatial and temporal scales (SHUGART 1998; WOOWARD 1987).

The forest ecosystem functions in structures at different biological complexity levels (Fig. 6).

Ecosystem response to environmental changes takes place at producer's level – in a tree leave and "spreads around", being strengthened or reduced by regulatory and compensation mechanisms, spreading the

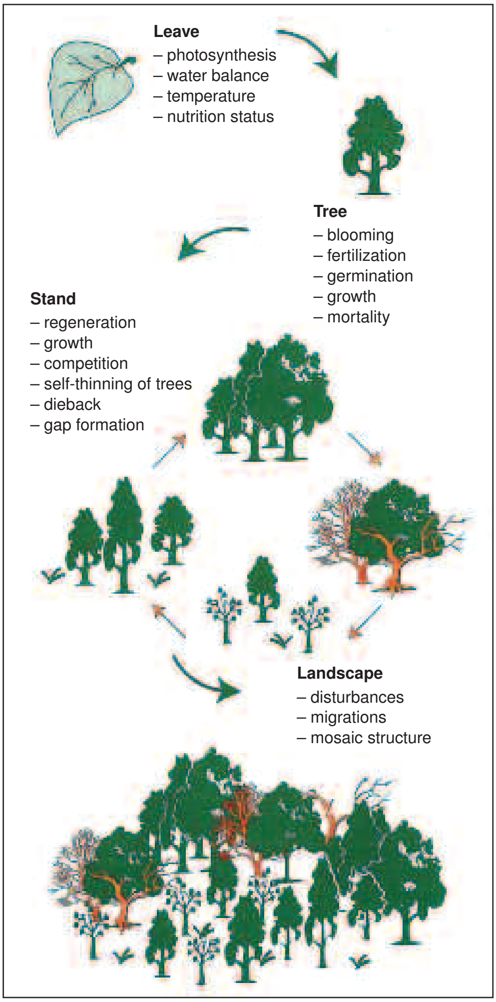

Fig. 6. Responses of natural systems to climate change at different organizational levels in a hierarchical structure

effect in multiple directions across the entire tree, stand and father on – to phytocoenosis, and through the energy used – onto consumers, reducers, whole biocoenosis, and from the ecosystem – onto the landscape. The response in a leave lasts as long as the photosynthesis reaction, yet changes in the occurrence of particular plant groups and in their ranges take much more time. To change their geographical location, species in late succession stages require a longer duration of the impact than pioneer species, even whole ages. However, even the tiny daily or monthly alterations have influence on flowering, seed production, germination, and consequently on species distribution. By reducing the time scale to hours, minutes or seconds, we can speak about disturbances in the physiological reactions of cells and tissues at the level of photosynthesis, respiration, closing and opening of stomatal pores, etc. Even small climate changes deeply alter the functioning of the organic world, penetrate into its mechanisms and modify its processes; their damage or disfunction is not manifested at once and can remain unnoticed, while the observed changes are attributed to other, known factors whose effects we knew before and which we know how to interpret.

This is a probable cause of the recent increase of insects, so called “secondary pests”, in coniferous stands. It would be by all means interesting to investigate the ecophysiological status of spruce stands attacked by the European spruce bark beetle from this point of view. According to the forecasts concerning changes in the occurrence ranges of Poland’s species (Fig.6 – model simulation) in the light of climate change (temperature and precipitation), Norway spruce (*Picea abies*) changes its ecological optimum moving northwards and eastwards. Trees exposed to such changes show a reduced resistance to biotic threats, increased susceptibility to pathogenic factors, and are naturally exposed to intensified attacks of their natural enemies. The biological structures which do not follow up with environmental changes or have lost such skills are thus eliminated. If the above hypothesis is true, then the persistent combat against bark beetles is erroneous and one-sided, regardless whether the protected stand is a commercially managed forest or a forest reserve.

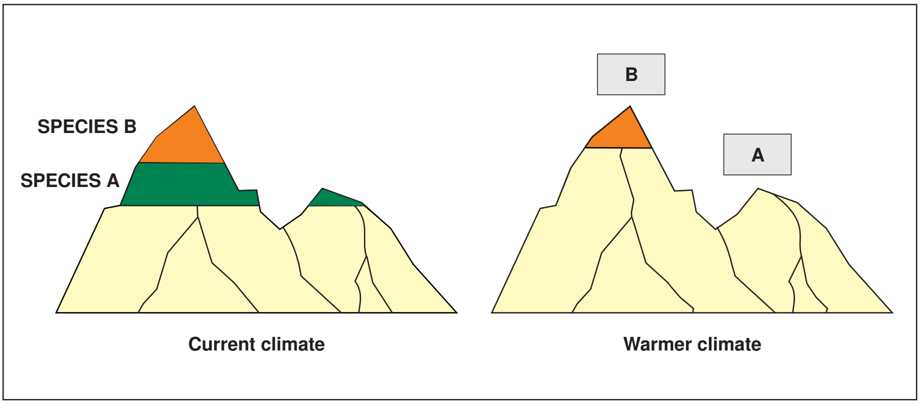

Fig. 7. Changes in vegetation zones in the mountains as a result of climate warming. Climate warming has caused retreat of species "B", while the favourable conditions have caused its replacement by species "A" (according to MALCOLM, PITELKA 2000)

Similar observations have been made in the mountains, where climate warming alters the recent vegetation zonation system (Fig. 7). The northward and upward shift (to upper locations in the mountains) of the current tree species ranges seems to set the direction of change of forest locations associated with climate change.

There are also other grounds for this interpretation. Working Group II of the Intergovernmental Panel on Climate Change (IPCC) of the Framework Convention on Climate Change (FCCC) noted in 2001 that boreal forests, that is Northern Hemisphere forests, as well as upper montane forests, with predominant coniferous species, were affected by climate changes in the first place and that their condition deteriorated (GITAY *et al*. 2001). Earlier, in the first report of the IPCC (1995), it was stated (WATSON *et al*. 1995) that nearly one third of global forest vegetation on average (and sometimes one seventh to two thirds, depending on the region) changed from coniferous to broadleaved forests due to increased temperature, water availability and increased concentration of atmospheric CO_2. Similar observations were also made in Poland (KOWALSKI 1993).

Of course, these interpretations assume that plant responses to the changing growth factors have not changed, only the growth factors have changed.

Climate change and the shift of climate zones can be faster than the changes taking place in plant communities. This is of key significance for the location of natural forests. However, this issue is less valid for plantations and managed forests where foresters can plant trees and saw seeds commensurate to the climatic requirements of species, however on condition that recognition of these requirements done in the past, reflects the current status (DAVIS, SHAW 2001).

Phenomena such as tree seed migration, changes in the spread of pests and diseases and fires also have an impact on forest location changes. Allowing such spontaneous changes, that is not preventing them through silvicular treatments seems to be rational and may assist to save many species from extinction.

6. Climate change versus forest productivity

Changes at photosynthesis and species composition levels are certainly reflected in ecosystem productivity, that is timber growth. CO_2 is the main factor of photosynthesis and its concentration affects plant productivity. Yet the correct assessment must be based on the interrelationships between CO_2 concentrations, temperature and water availability. These relationships are not fully recognized and improvement of one of the factors need not necessarily result in productivity growth (SHUGART *et al*. 2003). The transpiration mechanism steering the opening and closing of leaf stoma and regulating water economy in plants plays a big role here.

Research under controlled conditions has shown that for plants growing in the atmosphere with a double concentration of CO_2, that is approx. 660 ppm (with the other growth parameters remaining the same), the young plants produce approx. 40% more biomass, and the older and mature plants produce nearly 26% biomass. In the case of woody species, the combined effect of warming and CO_2 concentration increase may give a positive result. This relatively positive result of biomass production may however cause big changes in other elements of the forest ecosystem, such as species composition, biological diversity of other trophic levels, sustainability and resistance to health-threatening factors, etc. As the experiment under controlled conditions proceeded, the positive effect diminished.

The positive response of a tree leave to CO_2 concentration and its biomass growth do not immediately translate to biomass increment of a tree or whole stand. The higher organizational level, the more doubtful is the effect which spreads onto many substructures in the ecosystem's hierarchical structure. The observed response of a leave tissue and whole plant, as well as the interactive response of the ecosystem, demonstrating the positive effect of increased CO_2 concentration, is being reduced with the passage of time and organization level growth in natural systems (KORNER 1993), (Fig. 8). There are many causes of this, and usually they are inherent in the regulatory mechanisms whose recognition is still insufficient. One thing seems to be doubtless – the application of laboratory results to field conditions requires much prudence. And, secondly, the role of forests in accumulating more carbon amounts due to increased photosynthesis effectiveness requires further detailed analyses.

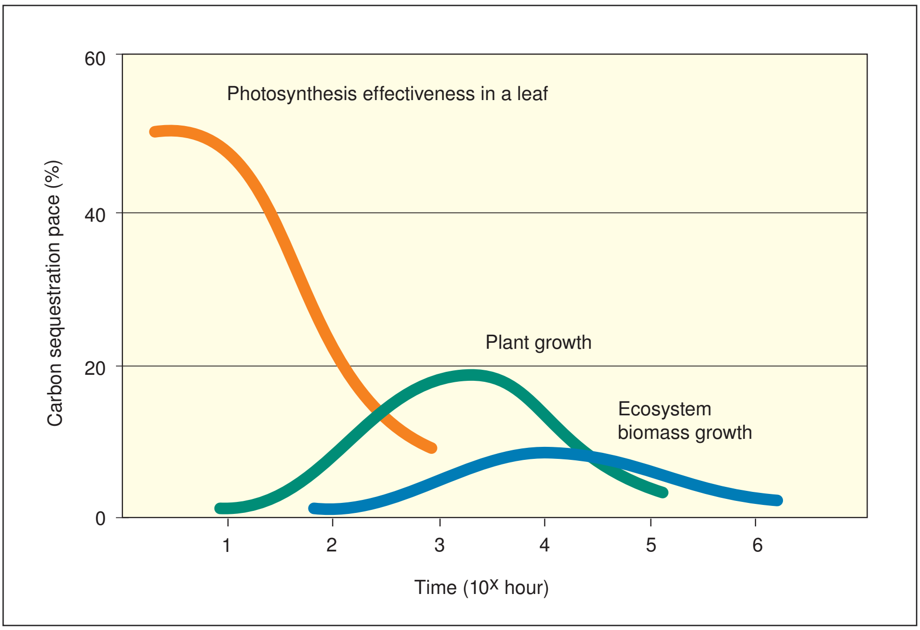

Fig. 8. Reduction of the productivity growth effect induced by increased CO_2 concentrations with the growing organizational level and passage of time (according to KORNER 1993). The time scale in Fig. 8 is expressed in hours to the power of x: if x = 1, the period is 10 hours, if x = 6, the period is 114 years

Recent studies (SCHLESINGER, LICHTER 2001) show that carbon growth in forest litter is also limited. An increase of carbon content in forests due to CO_2 growth in the atmosphere is limited by nutrient content in soil (OREN *et al.* 2001). To achieve a better result, forests should be fertilized and irrigated, which is irrational. The effect should also be limited.

As the response of plants to carbon dioxide concentrations in the atmosphere is uncertain, there is growing demand for physiological and autoecological research *in situ* on a representative network of permanent observation-measurement plots, designed for long-term interdisciplinary observations.

Few studies of this type (http://www.face.bnl.gov; http://www.esd.ornl.gov/facilities/ornlface/pce1999.htm; http://cdiac.esd.ornl.gov/programs/FACE/face.html), carried out both under greenhouse conditions and in the field, provide more details. After the first years, it was confirmed that additional carbon in the atmosphere caused by concentration growth is located in fine roots and leaves, rather than in trunks or stems, and that growth in Net Primary Production (NPP) cannot be a plant productivity indicator. A new edition of the BIOME-BGC program takes into consideration forest fires and extreme climate states, such as draughts and winds (http://www.forestry.umt.edu/ ntsg/).

Other reports (2005) confirm the scepticism as to the possibilities of accumulation of additional amounts of CO_2 by forest trees and acceleration of their growth due to increased carbon dioxide concentrations in the atmosphere (Scientific American, August 26, 2005; http://www.sciencedaily.com/releases/2005/08/050809064251.htm). Researchers from the Duke University in Canada stated that if an increase in the concentration of CO_2 in the atmosphere is accompanied by simultaneous climate warming and drying, no increased carbon retention in forests should be anticipated; on the contrary, its resources should diminish. In his studies, KÖRNER (2005) from the University in Bazylea (Switzerland) did not observe any increased wood and leave biomass production after increased concentration of CO_2 in the atmosphere. What he observed was an increased rate of exchange of carbon with the atmosphere. At the same time, he noted the possibility of increased root production and location of additional carbon amounts in the belowground biomass.

Recent years have seen extensive comparative studies in the USA on the existing climate models under the VEMAP Project (*Vegetation/ Ecosystem Modelling and Analysis Project*). (VEMAP 1995; MALCOLM, PITELKA 2000). Six ecological models differing in parametric requirements, yet sharing the advantage of dynamic forecast, were compared. The results appeared to be extremely divergent.

This strong diversity concerned first of all the structure of forest formations at landscape level, degree of forest cover, northward shift of forest formations, increase of areas with predominant savannas, decline of boreal mixed forests, etc. The multiple of mutually excluding changes makes such simulations of little usefulness for planning forest management behaviour strategies. However, it documents a significant lack of knowledge of large vegetation formations' responses to the changes of vegetation conditions.

There are many uncertainties in forecasting forest condition in a span of e.g. one hundred years (e.g. rotation). The models based on biogeochemical cycles (e.g. BIOME-BGC, TEM, CENTURY (AUCLAIR 2003) predict the Net Primary Production (NPP) value. However, the relationship between the NPP and stand productivity is not straight-lined. It is clear that a 20% growth in the NPP does not mean a 20% growth in timber production. An increase in primary production entails an increase in the losses due to the activity of consumers, particularly insects, as well as diseases and competitors, fires, winds or hardly predictable events. Those events are generally not taken into consideration in contemporary models. Neither are the effects of selection, fertilization, conservation, etc. included in the models. As we know, young trees respond more intensely to climate change, and their share in biomass growth is marginal.

Uncertainty of vegetation changes entails even higher uncertainty in determining the impact of climate change on the productivity of forest ecosystems. According to the analysis of photosynthesis effectiveness and its impact on tree and ecosystem biomass, expectations of productivity growth must be limited by the periodicity and transitionality of this process. Moreover, growth in the frequency and extent of natural distortions, like fires, strong winds, low or high temperatures occurring in atypical periods, draughts, floods, etc. may appear to be another important factor. As disturbances occur on a spatial scale exceeding the scale of any ecosystem studies, and their time intervals are much longer than the longest ecological studies, it is very difficult to assess their impact on forest ecosystems. These phenomena have not been sufficiently taken into consideration in the existing models dealing with the impact of climate change on forests.

7. Carbon management strategies in forests

The total amount of accumulated carbon in forests depends on:

1) species composition in a stand,
2) habitat conditions,
3) management (tending cuts, felling age or rotation cycle),
4) climate conditions (temperature, moisture).

Forest management can efficiently influence the first three factors through different management methods.

The impact of different management methods is illustrated in Fig. 9.

Natural forests show a maximum growing stock and zero (0) increment; selectively utilized natural forests show reduced growing stock which is set off by small increment. Commercially managed forests

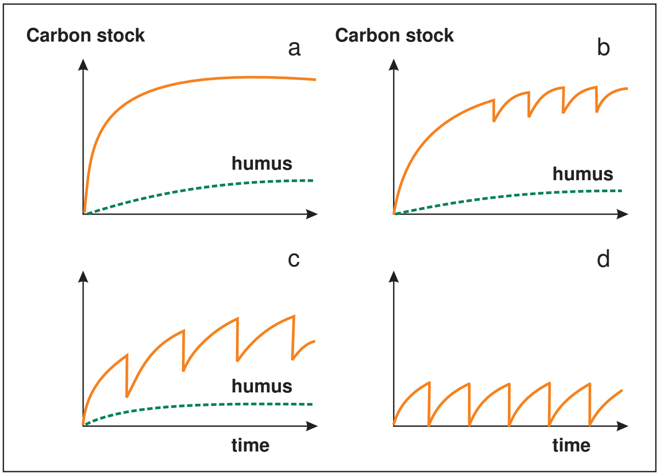

Fig. 9. Carbon stock and increment (a) in natural forests, (b) in selectively managed natural forests (c) in managed forests, (d) in plantations (according to WBGU 1998)

feature a 40% lower growing stock compared to natural forests, however despite their utilization, they have a greater growing stock than increment, as the harvest does not exceed the increment. In plantations, there is about 10-15% of natural forests' growing stock and the stock does not increase, for all the increment is harvested.

The applied management methods, or rather forest management's possibilities of impacting carbon accumulation, may serve for drawing the main carbon management strategies in forests (Table 1).

It should be emphasized that the current assessments of potential carbon sequestration are burdened with many doubts. First, the uncertainty derives from the socio-economic and technical barriers, second, many indirect effects on carbon accumulation in forests resulting from forest management are still unknown, and third, it is difficult to compare the economic and energetic effectiveness of substituting fossil energy sources with wood.

Table 1. Strategies, proposed measures and possibilities of forest management to reduce greenhouse gas concentration (according to CANNELL 1995; IPCC 1996)

Strategy	Proposed measure	Carbon concentration reduction potential to 2100 Gt
Protection and consolidation of existing carbon resources (reduction of indirect negative effect of forest management on forests)	Protection of forests on threatened areas	40–80
	Reduction of socio-economic pressure and deforestation prevention	
	Improvement of forest management through appropriate management: protection against pests, fires, boosting incremental growth, etc.	
Accumulation of carbon in new forests	Reconstruction of degraded forests	20–30
	Establishment of new semi-natural forests (afforestations)	
Substitution of fossil fuels and materials requiring large amounts of energy	Establishment of forest energy plantations	50–200
	Development of agro-forest farms	
	Application of biofuels generating electricity and heating	
	Substitution of cement, metals and plastics with wood	

Nevertheless, three principal lines of procedure can be defined:

1) protection of the existing carbon resources and their consolidation; this concerns both the protected natural forests and managed forests based on the principle of Sustainable Forest Management (SFM)
2) creation of new carbon sinks through afforestation, plantation management, farmland afforestation management and rehabilitation of degraded forests;
3) use of wood in substitution for fossil fuels and materials whose production requires huge amounts of energy (metal structures, cement, plastic), establishment of energy plantations with short production cycles, use of biofuels, etc.

Certainly, these strategies are not mutually exclusive. The initiatives to increase carbon absorption and extend the time of carbon retention have already been taken, like for example the FCCC and Land Use Change and Forestry (LUCF) projects under the name Activities Implemented Jointly (AIJ).

Ad 1. In natural, unutilized forests, the carbon cycle is in fact closed (Fig. 10). For the strategy of managing this terrestrial carbon pool, the most essential thing is to preserve the achieved equilibrium status. At the same time, it should be remembered that the possibility to increase carbon content or increment in those forests is in fact nonexistent. Similarly small impacting possibilities occur in the case of moderate, selective use of natural forests. It can be said that the existing carbon management tools for this type of management are sufficient to preserve the stock and control its use at the required level. The largest number of

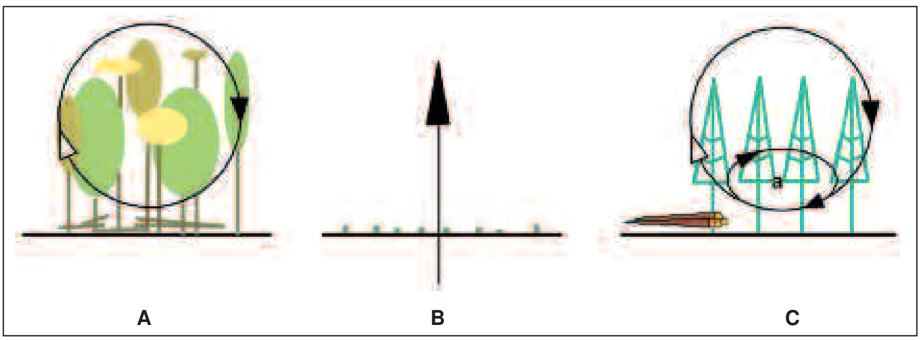

Fig. 10. (A) Closed carbon cycles in natural forests, (C) in managed forests, (B) carbon emission as a result of deforestations; a – utilization of wood and wood products (carbon recycling)

management tools are provided by sustainable forest management (Fig. 10, Option C) which enables stock growth, sustainable wood utilization and carbon pool preservation in products as a result of substitution of other materials. Like in natural forests, closing the carbon cycling in managed forests, where carbon is recycled in the form of wood and wood products (Fig. 10C) should be a theoretically possible target solution.

The largest potential counteracting rapid climate changes is in the preservation of the existing carbon resources in forests. The majority of carbon emissions caused by deforestation appear relatively soon after felling. Reduced felling will bring a beneficial change in the level of atmospheric CO_2 sooner than afforestation or forest regeneration. The latter operations may cause accumulation of similar amounts of carbon, yet in a much longer time.

It is estimated that should deforestation be totally stopped, 1.2–2.2 Gt of carbon more could be accumulated (DIXON 1993). BROWN (1996) estimates that reduced felling in tropical forests might probably save 10–20 Gt of carbon (0.2–0.4 Gt per annum) by 2050. However, as long as revenues from deforestations and incorrect forest use are one of the major drivers of economic development in the developing countries, their policy must take into consideration the causes of poverty and seek other ways of satisfying needs, if forests are to be protected.

Retention of carbon resources in the existing forests can be achieved by improving the existing management techniques. Reduction of carbon losses in the logging processes, that is the use of technologies reducing the impact of logging operations (*Reduced Impact Logging)* on carbon release, might be the most important factor. The conventionally performed logging generally cause a high amount of damage, particularly in the tropics (KURPICK, KURPICK, HUTH 1997). The new technical achievements (RIL) may reduce the degree of stand damage after felling by 50% (SIST *et al.* 1998) thus reducing the level of carbon emission associated with logging. NABUURS and MOHREN (1993) calculated that the long-term retention of carbon resulting from the RIL can, in tropical forests, reach 73–97 tons per hectare. Knowing those data and estimating that 15 million hectares of tropical forests, the majority of which are considered poorly managed forests (POORE *et al.* 1987), are cut every year (SINGH 1993), the potential growth of carbon resources in forests is tremendous. The problem is how to calculate these additional amounts of accumulated carbon left in the forest due to the introduction of new logging techniques (IPCC 2000).

Ad 2. The positive effect of carbon accumulation as a result of afforestation is not always clear. It depends on the afforestation technique, particularly on soil preparation.

After the afforestation of post-agricultural areas, carbon increment is not high, and can even be negative (DOWYDENKO 2003). The carbon accumulation process in afforested, post-agricultural soils proceeds in two stages: (1) in the first stage carbon is emitted to the atmosphere (2) in the second stage carbon is accumulated in soil during the further processes of stand growth.

The carbon emission stage, that is the negative carbon balance status caused by afforestations, is associated with soil preparation operations preceding afforestation, which affect its structure, like furrowing, deep ploughing, subsoiling, contributing to carbon oxidation and emission.

The period of carbon reduction in soil is followed by its growth and accumulation (Fig. 11). When a tree (stand) is close to maturity, the increment and sequestration rate slows down and can even drop to zero.

The possible amount of carbon accumulated as a result of afforestations (regenerations) is diverse and depends on the species, habitat or management method. The average annual afforestation output, expressed in tons per hectare, ranges from 0.8 to 2.4 tons in boreal forests, from 0.7 to 7.5 tons in temperate climate zone forests, and from 3.2 to 10 tons in the tropics (BROWN *et al*. 1996). Potential accumulation of carbon in agro-forest plantations is even more diversified depending on the nature and targets of production.

Assuming that the global area available for afforestation and agro-forest activities is 345 million hectares, BROWN (1996) estimated that about 38 Gt of carbon could be accumulated over the next 50 years – 30.7 Gt through afforestation and 7 Gt through the adaptation of agro-forest practices. A close look at the tropical regions allows concluding

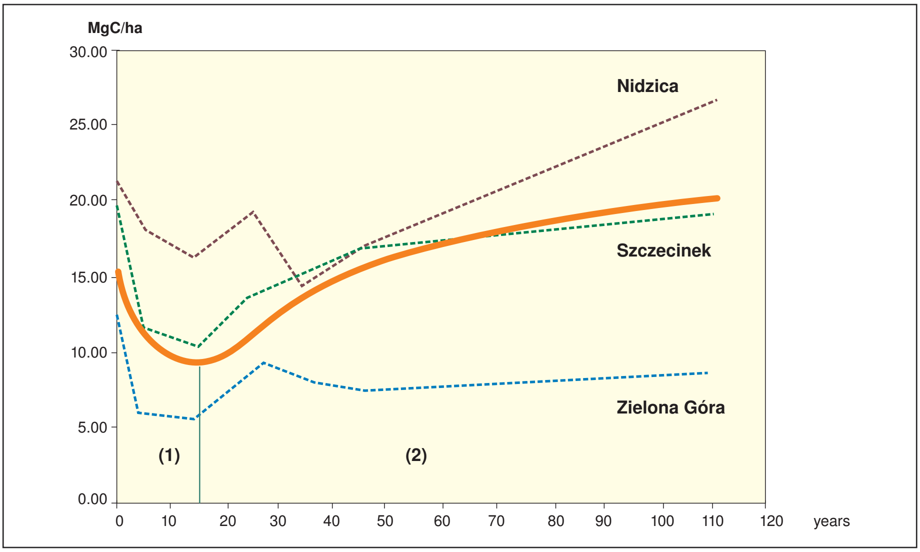

Fig. 11. Contents of carbon in soil in post-agricultural areas by afforestation age in Poland (DOWYDENKO 2003)
1) period of carbon content decline (emission)
2) period of carbon accumulation in soil (sequestration)

that additional 11.5–28.7 Gt of carbon can be obtained as a result of regeneration of 217 million hectares of degraded land (FAO 2001).

The land currently available for forestry will turn to be much smaller after taking into consideration all the social and economic aspects, as no more than one third of ecologically suitable land can if fact be utilized (HOUGHTON, UNRUH and LEFEBRVE 1991). According to this scenario, afforestation and agro-forest activity will absorb approx. 0.25 Gt of carbon, and the restoration of damaged land – the next 0.13 Gt of carbon per annum.

Ad 3. The global consumption of wood has increased over the past 25 year by approx. 40%, reaching 3.4 billion m^3 in 1994. The value of this wood was nearly USD 400 billion; approx. 75% of wood was industrially processed (FAO 1994). More than half of the wood is used as fuel; for two fifths of the people in the world, charcoal is the main source of energy (FAO 1997).

Biofuels currently supply 14% of the total energy requirement. In the developing countries, these satisfy one third of the energy requirement. If the current biofuel consumption is substituted by fossil fuels, the additional amounts of carbon emitted to the atmosphere would be 1.1 Gt per annum (IPCC 2000). Unlike fossil fuels, the use of biofuels does not produce CO_2 emissions (net) to the atmosphere (CO_2 released to the atmosphere from burning biofuels is used by the regrowing biomass). The replacement of fossil fuels by sustainable biofuels reduce CO_2 emissions proportionally to the value of substituted fossil fuels. The anticipated future share of biofuels in satisfying the demand for energy should oscillate from 59 to 145 x 10^{18} J in 2025 and from 94 to 280 x 10^{18} J in 2050 (BASS 2000). The future consumption will depend on technology development which will enable effective use of biofuels, such as use of the gas generated from wood products.

The new “biofuel plantations” will bring long-term positive results, if they substitute the current plantations featuring a lower pace of carbon accumulation. In the long term, the mean carbon density (carbon content per unit area) in plantations oriented on biofuel production (this particularly concerns plantations with short production cycles) will of course be higher than in the majority of unforested areas. The situation will be opposite when natural forests are substituted by biofuel-oriented short-rotation plantations: the positive substitutive effect will disappear due to the change in the land-use form – *i.e.* emissions caused by deforestations.

Utilization of wood and wood products as substitutes, that is in place of the materials whose production entails large emissions of carbon dioxide (like cement, steel, aluminium, or plastic), may also lead to a significant net reduction of CO_2 emissions. A good illustration of that is the comparison of energy and contamination potential both in wood and steel when building a 3 m high and 30 m long wall of identical thickness, using those two materials (MEIL 1995). By using wood, approx. 3.5 times less energy is used and nearly 3 times less CO_2 is emitted to the atmosphere, not to mention other gases whose emissions are multiple times smaller. In this way we reduce the greenhouse effect by about two thirds, consume about 20 times less water, without contaminating it, but contributing to its biological filtration. Such is the climatic and environmental sense of wood promotion.

8. Polish forestry's participation in climate protection

8.1. Poland's forests represent approx. 0.002% of the global forest resources, so their impact on global climate from this perspective is irrelevant. However, the sense of responsibility and participation in the common effort aimed at the improvement of human activity, including forest management, in order to restrain climate change and mitigate its effects, is significant. The participation of forests in the regional and local land use structure and local topoclimate shaping is of great, measurable importance.

Polish forestry faces an extraordinary effort towards continuous augmentation of forest cover and maintaining forest utilization at a level below wood increment. These are the simplest and most measurable forest management activities in favour of timber growth. Since 1946, forest area has increased by about 2.5 million hectares (in some years, even 60 thousand hectares of forests were added), while usage has never reached the increment level, oscillating between 55% and 70% of increment.

Changes in the nature of forest management in Poland and the evolution of forestry based on raw-materials towards sustainable forest management (The State Policy on Forests, 1997), foster climate protection activities and activate efforts increasing carbon accumulation in forest ecosystems. The appropriate silvicultural activities under the SFM program, which improve productivity, may to some extent increase the accumulative abilities of forest ecosystems (BERNADZKI 1993;

RYKOWSKI 1999, 2000), (the possible range of absorption increase is given below in parentheses):

- stand conversion towards species compositions better adapted to habitats (approx. 20–25 tC/ha);
- introduction of underwood (improvement of growing stock – appox. 1.1 m^3/ha/year and carbon accumulation e.g. beech underwood – approx. 0.4 tC/ha/year);
- change of the management system from clear-cutting to shelterwood and from artificial to natural regeneration (clear cuts cause release of about 24 tC/ha, on poor soils approx. 15 tC/ha; abandonment of the clear-cutting method of management may cause accumulation of an additional amount of approx. 0.4 tC/ha/year);
- efficient tending cuts, particularly thinning, in the way enabling use of timber from increment thinnings (hard to assess in terms of volume);
- afforestation of post-agricultural land (approx. 80 tC/ha, 60 years of age).

Under Polish forest conditions, we can assume that forest management practices may cause an increase of carbon accumulation as a result of stand conversion by about 200–215x10^6 tC; as a result of the introduction of underwood – by 16–20x10^6 tC, and due to afforestation– by about 80–240x10^6 tC.

The problem however is that this growth is very difficult to document and separate from carbon accumulation growth caused by natural processes, independent from human activity. This might be possible only through steady monitoring and comparison of relevant data from managed forests with those from reference forests without management intervention. There is urgent need that the State Forests NFH calls into being a network of such forests (RYKOWSKI 2003).

8.2. Recently, the State Forests NFH, the main administrator of Polish forests owned by the State Treasury, has started a series of research-application programs aimed to fulfill the obligations resulting from the Framework Convention on Climate Change and the possibilities of using the agreements laid down in the Kyoto Protocol.

A legislative proposal has been prepared specifying the legal--financial instruments to support the reduction of greenhouse gases and other emissions.

A broad spectrum of analytical work has been commenced with a view to determine carbon content in different tree fragments and different forest ecosystem elements. The target is to create allometric equations and verify empirical equations and calculation coefficients in order to determine the amount of tree biomass in the main forest tree species. The methods of determining the amounts of carbon accumulated in stands and forest complexes, as well as changes in carbon accumulation and its dynamics associated with a given form of management will also be the effect of this analysis (STRZELIŃSKI *et al.* 2008). The work on carbon content in herb layer on 530 forest biological monitoring plots in a 16x16 km grid was covered by an independent program. This is one of the most difficult elements of carbon balance in forests.

The attempt at estimating the net exchange of CO_2 between the forest and the atmosphere is a new approach to explaining the interreactions between climate change and forest ecosystems (OLEJNIK 2008). To this end, a 34 m high measurement station has been erected (Tuczno Forest District, central-western part of Poland – 53º11'N, 16º05'E) in an about 20 m high pine stand, where specialist equipment has been installed. An eddy covariance technique is used for measuring CO_2 flows. The main instruments used in this method include a spectrometric gas analyzer and ultrasonic anemometer for measuring wind velocity and direction. The equipment required by the eddy covariance technique has to measure the concentrations of water vapour, carbon dioxide and the vertical wind velocity component at a pace of 20 times per second. Due to such measurements, a huge database is created which requires specialist analytical procedures.

In addition to the need for content measurements and estimation techniques for carbon sequestration in forests, there is another issue to be dealt with- forest management adaptation to climate change. This is the task of another research program financed by the State Forests NFH. This program analyses first of all the silvicultural and forest management planning activities which affect the possibilities of adaptation of forest management practice to the changing environmental conditions and which may shape the size of carbon pool in forests and the rate of its sequestration.

9. Conclusions

9.1. Climate changes affect the condition, development and distribution of forests mostly through temperature increase and precipitation changes. All the regions with raised temperature and unchanged or reduced precipitation will suffer draughts which will affect vegetation growth and increase fire hazard. Fires are those factors which may become the highest threat to forests in those regions.

The existing forests may for some time sustain under the changed conditions. Their duration will depend on the adaptive skills of trees. However, changes in their natural occurrence ranges should rather be anticipated. The adaptive skills of trees, organisms with long development cycles will clash, over the period of one generation, with changes of temperature, CO_2 concentrations, soil moisture, habitat eutrophication (deposition of N compounds). Their ecophysiological responses will depend on the intra- and inter-species variability. They will also depend on interspecies relationships and ecosystem processes of: spread and preservation of pollinating species, plant consumers, insects, fungal diseases, other pathogenic factors, etc. Also properties unknown so far can come into play, and the whole system may respond in the way that today is hard to predict. Mountains will probably be important refuges for many species. Changes in species distribution may lead to new species compositions in forest communities and to their extinction. Changes in the quantity and quality of forests will affect, as a feedback, the acceleration of the occurring changes.

Uncertainty as to how biosystems will behave and unpredictability of nature seem to be the main defects of all scenarios describing nature's future states resulting from climate change.

9.2. Forests occur in a quadruple role in the climate change process:

1) as "the cause", that is as a source of greenhouse gases, mainly CO_2, as a result of deforestations,
2) as "the victim" of climate change causing increased vulnerability to pests and deseases, increased forest fires, changes in species composition, changes in the natural ranges of tree species,
3) as "the beneficiary" of climate changes, that is benefiting from the "greenhouse effect" temporarily stimulating biomass growth,
4) As "the remedy" for global changes and poor condition of the environment on account of: ability to absorb and accumulate carbon in forest ecosystems' structures (wood, soil), wood's substitutive properties for construction materials and raw materials, as well as fossil fuels, and the ability to regenerate for the benefit of the environment.

Thus the role of forests and forest management depends on the forest management methods and targets, as well as on the ways of utilizing forest goods, particularly timber.

9.3. The likely changes of climate characteristics will cause, in the longer perspective, deep distortions in the directions and pace of ecological succession which will shape forest ecosystems, commensurately to the ecophysiological sensitivity of tree species to the "greenhouse conditions". Many of the created change models anticipate disappearance of some and promotion of other tree species, as well as shrinking of forestland with its current structure and functions, at least on a regional scale. Forest communities will undergo radical changes. Elimination of some autotrophic species and development of others will cause fundamental changes in the trophic change structure, entailing hardly predictable quantitative and qualitative changes in forest biodiversity at all organizational levels. If these changes proceed in accordance with the predictions (the “wet variant” and the “dry variant” should be taken into consideration), we will have to do with structurally and functionally new forest ecosystems. This may radically alter the concepts and recent strategies of forest management development.

9.4. On the basis of available knowledge, it is possible to predict the likely changes in forests as nature’s structures, and forest management as a human activity in forests, in connection with climate change. Future studies will certainly verify these statements.

1. Natural species occurrence ranges will change, and these changes will be quasi-natural: with the rising temperature, the main forest tree species will migrate northwards, and towards higher altitudes in the mountains. This will entail changes in the structure of entire forest ecosystems and forest types.
2. Changes in ecosystem productivity are anticipated; these changes will be positive and negative as well. Forests may become, at least temporarily, more productive depending on the scale of temperature and precipitation changes, tree responses to higher CO_2 concentrations in the atmosphere, or mortality level. Many of these factors may vary depending on the region, forest type, species, etc.
3. The effect of increased CO_2 concentrations is particularly significant, complex and at the same time largely uncertain. Many assessments indicate an increased biomass increment and productivity growth, should the “fertilization effect” occur, at least periodically. The “carbon fertilization” effect at ecosystem level will be reduced by competition, insufficient level of other nutrients, or disturbances (insects, diseases, fires, winds, etc.).
4. An increase should be assumed in the frequency and level of disturbances in forest development, such as winds, fires, draughts, pests, diseases, etc. Adjustments should be introduced to the strategy of forest protection against biotic threats (particularly against secondary pests, noxious species, weakness diseases, etc.), as well as against abiotic factors (fires, winds, draughts, floods, extreme temperatures, season shifts, etc.).

5. We should anticipate growing timber production and relatively falling prices on the timber market. However, this depends to a large extent on the degree of timber utilization as energy biomass, which may contribute to timber price growth.

9.5. Poland lacks a governmental program or a national strategy (or a document of a similar rank) encouraging scientific, economic and political circles to initiate undertakings aimed at counteracting or adapting to climate changes. Actions mitigating the effects of such changes or adapting forest management to them have recently been undertaken by the State Forests NFH.

The medium- and long-term forest planning foresees actions consisting in moderate reconstruction of stand structures, from coniferous to mixed or broadleaved forests, maintaining rational forest utilization (stock-increment-yield) and promotion of wood as a product protecting climate. The commenced works aim to formulate a climate change adaptation strategy for forest management which foresees the following silvicultural - protective measures: introduction of a second storey, introduction of underwood, adaptation of tending cuts, increase of carbon retention in soil and protection of organic matter, reduction of soil structure disturbances, preferences to natural regenerations, multidirectional timber promotion, particularly long-term wood and wood product management, afforestation of new areas and promotion of landscape afforestation, etc.

Retaining the representative forest areas, free from economic intervention and exposed to spontaneous adaptation processes, and transferring the knowledge acquired there to other managed areas (reference forests) should be important elements of the strategy.

The above tasks to be undertaken by forest management require scientific support, particularly determination of their effects on other forest management goals and forest functions.

9.6. In spite of some major doubts and concerns about the future of forests, the completed analyses and assessments justify formulation of the following assumptions for the forest management strategy to mitigate the effects of the anticipated climate changes.

1. Afforestation of post-agricultural land and wasteland; change of afforestation techniques by avoiding intensive soil preparation (ploughing), promotion of natural forest regeneration and seeding; optionally*:* use of suitable land in the afforestation process and introduction on a larger scale of "plantation forestry" with a shortened production cycle, at the same time ensuring sustainable timber utilization or its substitutive use (see: timber promotion).
2. Widespread introduction of the sustainable forest management principle:
   - Promotion of natural regenerations;
   - Limitation of clear cuts and reduction of their unit area;
   - Limitation of tending interventions, particularly mechanical soil preparation;
   - Increased intensity of tending cuts – on condition of sustainable timber utilization (see: timber promotion);
   - Soil protection and increase of organic matter retention in forest ecosystems (introduction of underwood, stand reconstruction, introduction of second storey);
   - Application of environmentally friendly forest utilization technologies, particularly those not causing damage to soil and stand:
   - Abandonment of burning slash;
   - Use of bio-oils in forest equipment and machinery.
3. Promotion of timber as a substitute for energy-consuming raw materials and products, as well as a direct source of energy – cooperation with the building, timber and power industries.
4. Extension of wood products' life cycle – their period of use should equal or exceed the production period.
5. Optional: increase of utilization to 70–75% of increment.

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