

**Rhine basin study: Land use projections based on biophysical  
and socio-economic analyses**

**Volume 3. Climate change impact on forest yield potentials and water use**

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## ABSTRACT

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Effects of climate change on forest yield potentials and water use were predicted, using biophysical process knowledge and literature data. The climate change scenario used comprised changes in carbon dioxide, temperature and precipitation. Water use was calculated as the sum of transpiration and interception, which were derived from annual dry-matter increase and precipitation. Three scenarios were developed for estimating the change in yield potential and water use of forest in the Rhine basin. Scenarios show that the yield potential may increase by 0 to 5% whereas the water use is expected to decrease by about 5%.

Keywords: carbon dioxide, interception, precipitation, scenario, temperature, transpiration

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## **Preface**

This report has been prepared by the DLO Winand Staring Centre in Wageningen under contract for Rijkswaterstaat RIZA (Institute for Inland Water Management and Waste Water Treatment) in Lelystad. It is a contribution to a large research project of the International Commission of the Hydrology of the Rhine basin (CHR/KHR), initiated in 1989, on the assessment of the consequences of changes in climate and land use for the discharge regime of the Rhine. Several institutes from the Rhine riparian countries are collaborating in this project. Coordination is in the hands of the CHR. On the Dutch side, work in the project is being undertaken by the Institute for Inland Water Management and Waste Water Treatment (RIZA) and Utrecht University (RUU). RIZA is also responsible for the development of land use 'scenarios', conceived as projections of future land use. This research has been subcontracted to the DLO Winand Staring Centre (SC-DLO).

In a preliminary biophysical study, 'Effects of climate change on crop production in the Rhine Basin' (WOLF & Van DIEPEN, 1991), also conducted by SC-DLO, simulations were done for a few climate-soil combinations only, by far not representing the diversity of biophysical conditions in the Rhine basin. Also forestry was not considered. In the present study both biophysical and socio-economic factors are considered for the development of land use projections.

Volume 1 presents a biophysical classification needed for identifying geo-referenced agro-ecological zones serving as a basis for region-wide land use projections under current and future conditions. Volume 2 describes the impact analysis of the possible climate changes on crop suitability and crop productivity, and in effect on land use patterns and water use. This volume - Volume 3 - deals with impact analysis on forest yield potentials and water use. Volume 4 describes the possible impact on land use in the Rhine basin of both biophysical and socio-economic developments, presented in a number of projections for decade 2040-2049.

During the study it soon became clear that in the projections a contraction of the total agricultural area was foreseen, so that the vacated area could be allocated to increased urban use, forestry or other land uses. As forestry occupies the lowest place in the land allocation hierarchy after urban and agricultural land use, the projections do not allow to estimate the likely future forest area, but it is plausible that the forest area will increase. In the context of the biophysical study the question remained to estimate the consequences of climate change on forest yield and water use. Therefore an estimation procedure was developed, which was applied to data from forest statistics at country level. A more detailed analysis on effects of forest composition, growth and water use at the level of biophysical regions was not feasible within the framework of the present study.

Kees van Diepen  
Project leader

### ***Acknowledgements***

This report has benefitted from inputs and comments from many colleagues. I acknowledge the discussions and comments received from Ir. Kees van Diepen, Dr. Reimund Rötter and Dr. Frank Veeneklaas of SC-DLO, and from Drs. Koen Kramer of IBN-DLO.

Also many thanks to Ir. Bart Parmet and Ir. Matthijs Raak (RIZA) for their support and counsel.

**Kees Hendriks**

Wageningen,  
September, 1994

## Summary

Originally most areas in the Rhine basin were covered with forests. After this period of decreasing forest areas, reforestation took place in the 19<sup>th</sup> and 20<sup>th</sup> century. These new man made forests were completely different from the primeval forests. Therefore the natural zonation of vegetation as given by Ellenberg (1978), representing the original forest types, has become less clear through human influence.

Although man plays a major role in present forest composition, climate (e.g. precipitation, temperature and ambient gas concentrations) plays a major role in forest growth and forest limits.

Elevation of ambient CO<sub>2</sub> has proved to increase assimilation rate of plants, by which gross production will also increase. At a climate change scenario of IPCC (Wigley and Raper 1992) with a doubled ambient CO<sub>2</sub> concentration, a temperature rise of 2°C in decade 2040-2049 and a rise in winter precipitation with 10%, estimated increase in dry matter for forests in the Rhine basin was 5%.

Present water use of forests in the Rhine basin was estimated by calculations on transpiration and interception. Under current climatic conditions transpiration was estimated at  $10.3 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$ , interception at  $14.0 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$  and total water use at  $24.2 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$ .

To estimate the range of change in water use of forests in the Rhine basin under elevated ambient CO<sub>2</sub> concentration, three scenarios have been developed. In the first scenario yield is supposed to increase 5% while TC remains equal. Second scenario contains an increase in yield of 5% and a decrease in TC of 20%. Third scenario comprehends an unchanged yield and a decrease in TC of 20%. In the first scenario total water use was estimated at  $24.8 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$ , 2% higher than current water use. The second scenario shows a total water use of  $22.6 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$ , 7% lower than at present. Third scenario shows a water use of  $22.2 \cdot 10^9 \text{ m}^3 \text{ yr}^{-1}$ , which is 8% lower than current total water use.

Predictions about change in water use of forests, generated by climate change, contain many uncertainties just like the predictions in climate change itself. Climate change can be divided into a change in ambient CO<sub>2</sub> concentration, temperature, amount and distribution of precipitation (spatial and in time), radiation and so on. These factors may affect plant growth and water use direct as well as indirect. This study was mainly focused on direct effects such as the CO<sub>2</sub> fertilizing effect and effect of temperature

rise on growth and water use of forests.

Considering that air pollution may reduce the growth stimulating effect of a doubled CO<sub>2</sub> concentration, it may be expected that forest growth will increase 0 to 5%. And further that, due to air pollution, the CO<sub>2</sub> induced decrease in transpiration losses may be less than in a situation without air pollution. The effect of climate change on the water use of forests in the Rhine basin is expected to be in the range of +2 to -8% compared to current water use, with an average change of about -5%.



# 1 Introduction

## 1.1 Background and objectives

Expected climate change according to IPCC consensus (Houghton et al. 1990, 1992, Barrow 1993) would most likely have considerable impacts on agriculture, natural vegetation, and the discharge of the river Rhine, with consequences for supply of drinking water, shipping, etc. Possible negative consequences could be minimized by an effective policy, founded on insight in the effects of climate change on the hydrological processes. Climate change may have direct and indirect effects on river discharge. For instance, changes in precipitation amount or intensity in the Alps would directly affect the risk of flooding. Indirect effects may result from its influence on land use in terms of crop choice and cropping calendar, and hence on crop water use, soil coverage, leaching to deeper soil layers and surface runoff. Thus, through its impact on land use, climate change may cause additional changes in the discharge pattern of the river Rhine.

Against this background, in 1989, the International Commission of the Hydrology of the Rhine basin (CHR/KHR) initiated a project to assess the consequences of changes in climate and land use for the discharge regime of the Rhine. Several institutes from the Rhine riparian countries are collaborating in the project. Coordination is in the hands of the CHR. On the Dutch side, work in the project is being undertaken by the Institute for Inland Water Management and Waste Water Treatment (RIZA) and Utrecht University (RUU)(Parmet 1993).

The central aim of the CHR climate change project is to develop a water management model for the whole basin with the capability of analyzing the impact of average and extreme discharges by using 'scenarios'. The use of scenarios is a way to cope with uncertainties. As uncertainty is inherent to predicting the future, various aspects of the future call for a scenariowise approach, e.g. the nature of the climate changes to be expected, alternative policies to combat the greenhouse effect, political, demographic and economic developments. Sometimes it is more appropriate to speak of projections rather than scenarios, as scenario implies a development pathway, while a projection refers to one point in the future.

One of the tasks of RIZA within the CHR project is to develop land use scenarios. This research has been subcontracted to the DLO Winand Staring Centre (SC-DLO). The present study aims at contributing to a better understanding of climate change effects on land use in the Rhine basin, resulting in the development of land use scenarios on the basis of both biophysical and socio-economic factors (Parmet 1993). The specific aim of the biophysical part of the present main study 'Land use projections for the Rhine Basin on the basis of biophysical and socio-economic analysis' is to come up with geo-referenced information on land use potentials under current and future conditions. The project proposal specified that as unit areas for the analysis should serve all land types which are represented by unique combinations of crop, soil, climate, and altitude. These can be determined only if a sensible classification for each of these factors exists.

The development of a consistent biophysical classification is the subject of volume 1. The second volume deals with the impact of climate change on agricultural land use potentials, and the present third volume with the impact on forest yield and water use. The possible spatial shifts of land use potentials are then compared with 'autonomous' or socio-economic developments (in the absence of climate change) in view of their relative importance for future land use patterns in the Rhine basin. Considerable changes in land use could also occur in the absence of climate change. Analysis of expected 'autonomous' developments and its main determinants for the Rhine basin are presented in the socio-economic part of this combined study (volume 4), concluding with a synthesis of both parts.

As there are several interactions between land use and climate change (interrelated side-effects, e.g. on soil thermal and moisture regimes), speed and direction of the former partly co-determines the latter and *vice versa*. The feedback mechanism, change in land use - acceleration/delay in regional climate change, is, however, beyond the scope of the present study.

## **1.2 Problems and priorities of the biophysical impact study for forestry**

The issues to be addressed by the present forestry study are the impact of climate change on timber growth, water use, and forest composition, and to take into account the plausible changes in forest areas as indicated in volume 4. The autonomous developments described in the projections indicated a contraction of agricultural land use. The land vacated by agriculture is then allocated first to comply to the need for urban land and the remaining land can be allocated to either other land use or forestry. It is expected that the total area under forest will increase.

As intended, information from literature was used to study these research topics. The effects of the most important climatic factors influencing forest growth and water use are discussed : temperature, carbon dioxide, and precipitation. Based on this information an estimation is made of the possible overall increase in tree growth. This estimate, combined with current forest growth statistics leads to an estimate of future growth rates. As there is often a linear relation between growth and transpiration, the forest transpiration could be estimated. After estimating the interception the total forest water use can be calculated. Incertainties in the estimates are caused by the incertainties in the factors considered, but also because of other factors, not taken into account in the estimation procedure, such as air pollution. These incertainties are discussed.

Within the time and manpower constraints of this study it was not feasible to use the biophysical classification in the same way as for the impact analysis for agriculture, and to make the analysis for all biophysical units distinguished in volume 1. In stead the more general analysis described above was done using as spatial subdivision the total forest area within the Rhine basin subdivided by country, without distinction by soil types or bioclimatic zone. It was assumed that the forest composition (deciduous-coniferous) would not change. Estimates of growth rates and water use were derived from

literature data, based on average conditions, not allowing to analyze regional and temporal variability.

### **1.3 Outline of the report and reader's guide to the biophysical parts**

The biophysical study is divided into three main parts:

- Part 1: Biophysical classification as a general framework  
(Volume, 1) (author: R.P. Rötter)
- Part 2: Climate change impact on crop yield potentials and water use  
(Volume 2) (authors: R.P. Rötter & C.A. Van Diepen)
- Part 3: Climate change impact on forest yield potentials and water use  
(this Volume 3) (author: C.M.A. Hendriks)

The socio-economic study and synthesis of biophysical and socio-economic analyses are contained in Volume 4 (authors: F.R. Veeneklaas, L.M. van den Berg, D. Slothouwer & G.F.P. IJkelstam).

Overview on volumes 1, 2 and 3

Volume 1 (author: R.P. Rötter):

The geographic description (chapter 2) and the overview on current climatic conditions, soils and land use/land cover types in the Rhine basin (chapter 3) are largely based on literature, while in chapter 4 account is given of the newly established bioclimatic classification system and the methods applied to arrive at biophysical land types.

Volume 2 (authors: R.P. Rötter & C.A. Van Diepen):

Chapter 2 deals with the uncertainties of (regional) climate change predictions and gives the scenario selected for the current study. Chapter 3 introduces the approach chosen for assessing land use suitability and crop production possibilities under present and possible future conditions.

Chapters 4 and 5 give the results, i.e. crop yield potentials and water use for current and future conditions, respectively, followed by a discussion (chapter 6), conclusions and perspectives (chapter 7).

Volume 3 (author: C.M.A. Hendriks):

In Chapter 2 past changes in forest land use are discussed. Chapter 3 deals with climatic factors influencing forest growth. Chapter 4 explains the impact of climate change on forest growth, presents procedures to estimate forest growth and related water use, and interception of rain water, and gives the results when applied to the parts of the Rhine basin located in different countries. Chapter 5 discusses uncertainties and conclusions.

## 2 Past changes in forests

Originally most areas in the Rhine basin were covered with forests. Only those areas which were too cold or too wet for forests, were open areas. Due to human influence most primeval forests have disappeared. Large areas have been cleared for agricultural land, fuel wood and timber. A very large amount of timber was needed for ship-building in the 15<sup>th</sup> to 19<sup>th</sup> century. The centre of this building activity was in the Netherlands, large amounts of timber were imported from Germany, especially from the Black Forest (Buis 1985).

After this period of decreasing forest areas, reforestation took place in the 19<sup>th</sup> and 20<sup>th</sup> century. These new man made forests were completely different from the primeval forests and also contained exotic tree species such as Douglas fir, Hemlock spruce and Japanese larch. Also native species were planted on sites originally wooded with other species. Therefore the natural zonation of vegetation as given by Ellenberg (1978), representing the original forest types, has become less clear through human influence.

Surely not only human but also climate influenced forest composition and growth. Temperature oscillations of the past, for instance the reconstruction made by Lamb (1984), show remarkable parallels with forest changes as documented by pollen records (Huntley and Webb 1988). From the 13<sup>th</sup> to 15<sup>th</sup> century mean annual temperature decreased from about 10.3 °C to 8.8 °C. Combined with an intensive land use this climatic change probably enhanced deforestation. In the North-West European lowlands large forest areas changed into eolian drift sand landscapes (Koster 1978).

### 3 Climatic factors influencing growth and water use of forests

As said in the foregoing chapter, present forest composition is dominantly man created. The ratio between coniferous and deciduous forest area, as well as the composition of tree species itself reflect the socio-economic use of forests. In most present forests, wood production is a major aim, or was until recently. Therefore high productive tree species have been introduced, dislodging native species. Last decades growing attention was paid to ecological processes of forests. Institutions of nature conservancy, but also other forest owners give way to native species. On the short timescale of several decades, this time dependent thinking about forest and its role for society is much more important to forest composition than climate change impacts. Also of great influence are new inventions of wood replacing materials, new applications of wood products and economic activity.

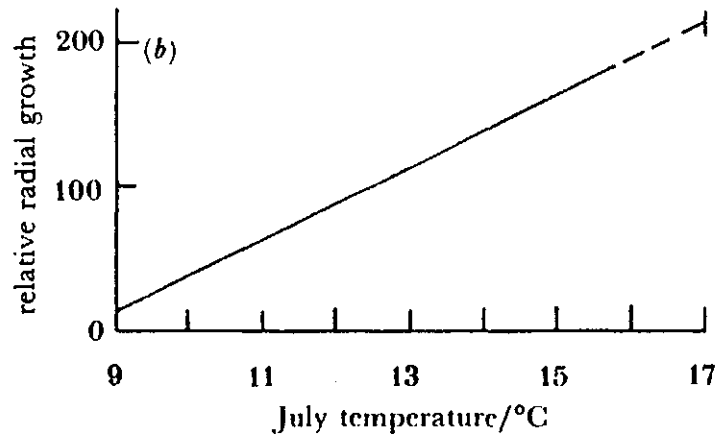
Although man plays a major role in present forest composition, climate plays a major role in forest growth and water use of forest.

#### 3.1 Temperature

Temperature is the most dominant factor limiting forest growth near forest limits . On high altitudes temperature effects clearly show as a forest limit. In general the timberline is increasing from North to South Europe. For instance the limit for Birch (*Betula pubescens* EHRH.) is about 200 m a.s.l. in Scandinavia and about 2000 m a.s.l. in the Western Alps (Mayer 1984). The form of the forests near the upper limit is very varied. It may be a sharp line against a treeless zone or a broad transition zone from dense forest to isolated, stunted individual trees. Therefore differentiation can be made between a forest-, tree- and krummholz-limit (Tranquillini 1979).

Temperature during the growing season plays a major role in the location of the timberline. The 10 °C July-isotherm agrees relatively well with alpine and polar timberlines (Tranquillini 1979). A closer agreement is obtained by the mean daily maximum temperature of 11.1 °C (Marek 1910).

Temperature not only determines tree limits, but also tree growth. Mikola (1962) showed a clear relation between July temperature and tree ring growth of Scots pine near the Finnish latitudinal tree line (Fig. 1). In the range of 9 - 16 °C the relation was linear and had a high correlation coefficient ( $r^2=0.8$ ).



*Fig. 1 Relation between relative radial growth of Scots pine in Finland and July temperature (°C) (Source: Mikola 1962).*

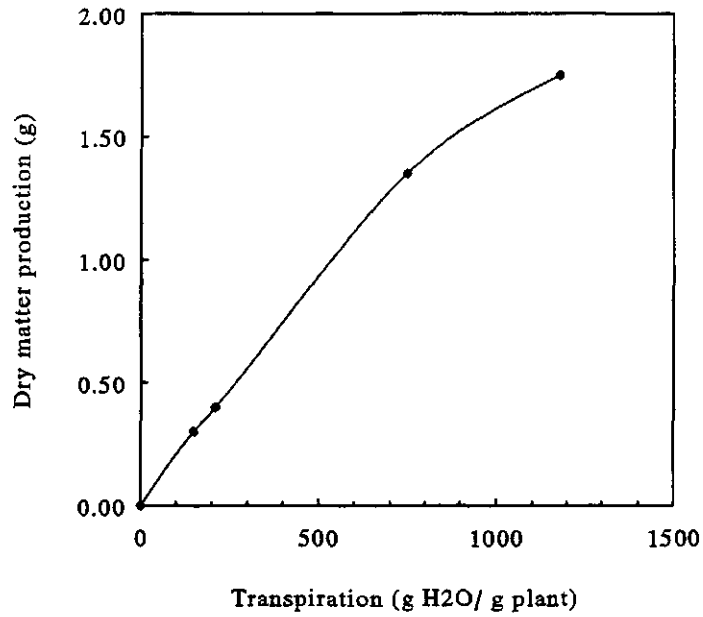
### 3.2 Precipitation

Besides temperature, precipitation is an important factor determining tree growth. Nonhebel (1987) simulated transpiration and interception for several tree species (Table 1). The total water use is the sum of transpiration and interception. Given figures were calculated for a sandy soil in De Bilt.

*Table 1 Transpiration (T), interception (I) and Water use (WU) of tree species in mm and percentage of annual rainfall (source: Nonhebel 1987)*

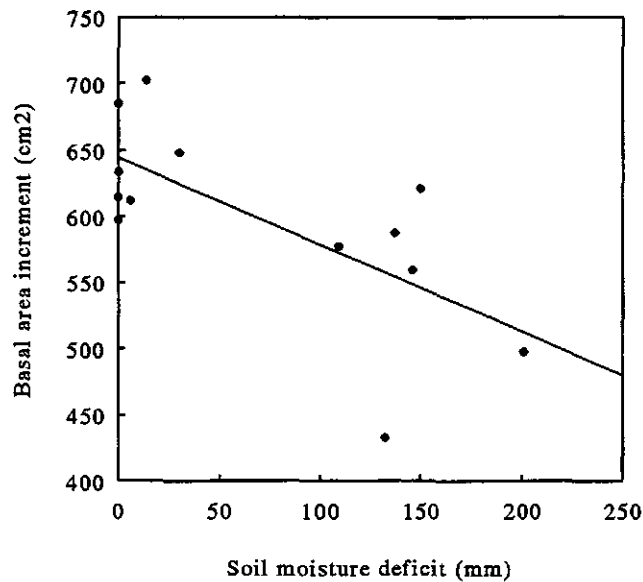
Tree spec.	T		I		WU	
	(mm)	(%)	(mm)	(%)	(mm)	(%)
Pine	189	27	186	26	375	53
Spruce	300	42	354	49	654	91
Douglas fir	237	34	334	46	571	80
Larch	206	30	135	19	341	49
Oak	286	41	122	17	408	57
Beech	211	30	114	16	325	46
Poplar	237	34	148	20	385	54

In a pot experiment Heinze and Fiedler (1980) found an asymptotic relation between transpiration and dry matter production of seedlings of Scots pine Fig. 2.



**Fig. 2** Dry matter production and transpiration of seedlings of Scots pine (after: Heinze and Fiedler 1980)

Since transpiration is related to precipitation and also to dry matter production, it may be assumed that dry matter production is also related to precipitation. This is confirmed by results of Greeven (1981) and Wösten et al. (1984) who found a relation between precipitation deficit and the relative radial increment for Scots pine in the Netherlands (Fig. 3).

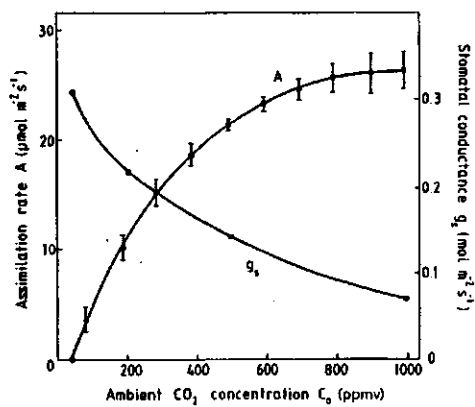


**Fig. 3** Relative annual basal area increment of 80 years old Scots pine and the annual precipitation deficit (after: Wösten et al 1984).

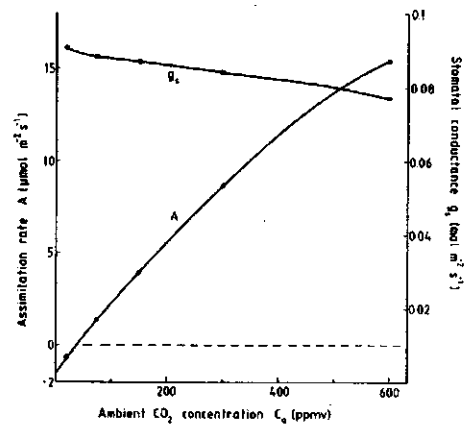
### 3.3 Ambient CO<sub>2</sub> concentration

It is known that the ambient CO<sub>2</sub> concentration strongly influences the assimilation rate (Fig. 4). The difference between Fig. 4a and 4b shows a species specific reaction on ambient CO<sub>2</sub> elevation. Both figures show the relationship between assimilation rate, stomatal conductance for CO<sub>2</sub>, and ambient CO<sub>2</sub> concentration. Fig. 4a shows the relationship for *Populus deltoides*. Measuring conditions were: quantum flux density 2000  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ; temperature 30 °C; water vapour saturation deficit 1.7 Kpa. In Fig. 4b the relationship for Sitka spruce is given, with measuring conditions: quantum flux 1000  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ; temperature 20°C; water vapour saturation deficit 0.6 Kpa.

(a)



(b)



**Fig. 4 Relationship between assimilation rate (A), stomatal conductance for CO<sub>2</sub> ( $g_s$ ) and ambient CO<sub>2</sub> concentration ( $C_a$ ) for unstressed *Populus deltoides* (a) and *Picea sitchensis* (b) (source: Bolin et al., 1986)**



## 4 Impact of climate change on forest growth and water use

If climate will change, this might be of great influence to forests. In this study we will restrict to growth and hydrological processes. Growth rates and tree limits may change caused by an elevated CO<sub>2</sub> level and temperature rise. But also possible changes in other climatic factors, such as solar radiation, precipitation and wind velocity, are of great importance, as well as the distribution of these factors over the year.

In volume 2 of this study (Rötter and Van Diepen 1994) a scenario of possible future climatic change was used to predict changes in crop growth and water use. Changes were assumed in temperature and precipitation for a 'Business as Usual' (BaU) scenario going from present day to decade 2040-2049 (Table 2).

*Table 2 Assumed changes in temperature and precipitation for the Rhine basin (Rötter and Van Diepen 1994)*

Climatic factor	Season			
	Winter	Spring	Summer	Autumn
Temperature (°C)	+2.0	+1.75	+1.5	+1.75
Precipitation (%)	+10	0	0	0

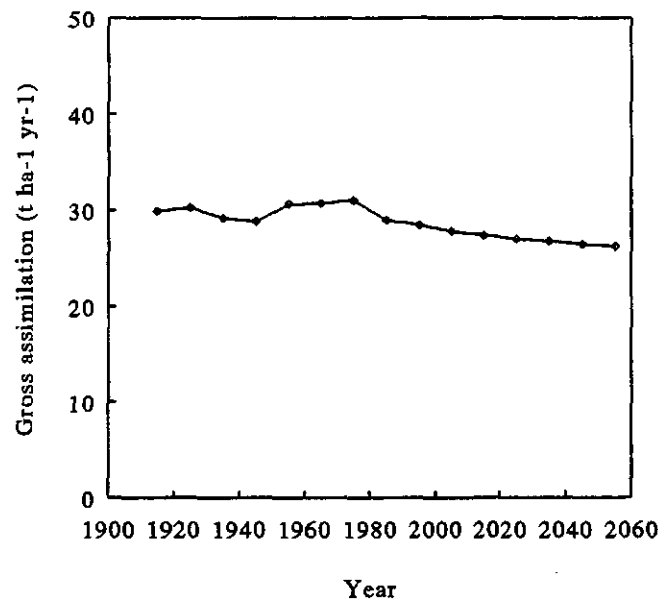
Also an elevated CO<sub>2</sub> concentration of ambient air was presumed, following the estimations of IPCC (Wigley and Raper 1992), from 353 ppmv at present to 560 ppmv at 2040-2049.

### 4.1 Effect of increased CO<sub>2</sub> concentration

A higher assimilation rate will increase the gross production. The change in net production is different from that in gross production because respiration losses may increase also. Experiments with agricultural crops in general show an increase in production with an elevated CO<sub>2</sub> level. For instance Dijkstra et al. (1993) found at a doubled CO<sub>2</sub> concentration (going from 350 ppmv to 750 ppmv) an increase in yield and above ground biomass of 34% and 35% respectively for spring wheat and of 51% and 58% respectively for faba bean. But it is not clear if such an increase also hold for forest production. Many authors give their doubts about translating results from short period experiments with annual crops to perennial crops such as forests (Shugart et al. 1986, Jarvis 1989). Nonetheless, Overdieck (1993) found an increase of 39% in mean net assimilation at light saturation for Beech when doubling the CO<sub>2</sub> concentration to 700 ppmv. In these experiments with greenhouses young Beech plants also showed an increase in stem diameter, stem height and leaf area index (LAI) of 13.5%, 27.4% and 40% respectively. Goudriaan and Unsworth (1990) mentioned an increase of 40% in the maximum rate of assimilation ( $A_{max}$ ) as typical for C<sub>3</sub> plants.

## 4.2 Effect of increased temperature

Kramer (1992), simulated the effect of an increase in temperature of 0.3 °C per decade from 1992 to 2060 on the assimilation and growth rate for beech and oak. The study showed a decrease in net annual assimilation due to a higher increase of maintenance respiration compared to the increase of gross photosynthesis (Fig. 5). This reduction, due to temperature rise, doesn't take into account the fertilization effect of an increasing CO<sub>2</sub> concentration.

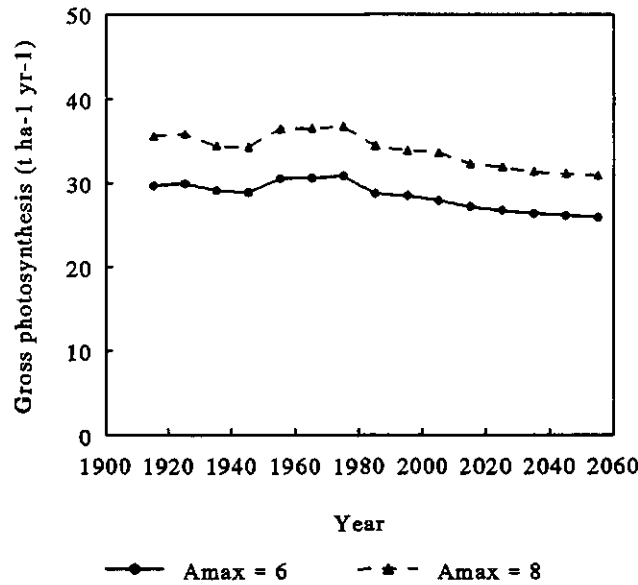


*Fig. 5 Assimilation rates of beech by increasing temperature (0.3 °C temperature increase per ten years, after: Kramer 1992)*

## 4.3 Estimation of forest growth and water use

### 4.3.1 Dry matter

If we, for our study, use an increase of  $A_{\max}$  of 40%, and we assume a rise in CO<sub>2</sub> concentration from 350 ppmv to 560 ppmv, we might expect an increase of  $A_{\max}$  of about 25% ( $0.40 \cdot (560-350) / (700-350)$ ). Kramer (1992) gives a present level of  $A_{\max}$  for beech of 6.3 Kg CO<sub>2</sub> ha<sup>-1</sup> h<sup>-1</sup>. So, this might become  $6.3 + 25\% = 7.8$  Kg CO<sub>2</sub> ha<sup>-1</sup> h<sup>-1</sup>. In the study of Kramer also a sensitivity analysis is given of  $A_{\max}$  for beech. It shows a higher rate of gross photosynthesis given a higher  $A_{\max}$  (Fig. 6).



**Fig. 6** Assimilation rates of beech for two maximum rates of photosynthesis ( $A_{max}$ , after: Kramer 1992)

Through interpretation we estimated that with an  $A_{max}$  of  $7.8 \text{ Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ , gross assimilation would be about  $30,5 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ , while at the level of 1992 ( $A_{max} = 6.3 \text{ Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ ) gross assimilation is estimated at about  $28.5 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ . Derived from data of Kramer (1990) maintenance losses were estimated for an  $A_{max}$  of  $6.3 \text{ Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$  and  $7.8 \text{ Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$  at  $9.5 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$  and  $10.5 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$  respectively. Net assimilation can be calculated as:

$$F_{nc} = F_{gc} - R_m \tag{1}$$

in which:  $F_{nc}$  = net assimilation ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ )  
 $F_{gc}$  = gross assimilation ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ )  
 $R_m$  = maintenance respiration ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ )

Hence  $F_{nc}$  will increase from  $19.0$  to  $20.0 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ , an increase of about 5%.

The rate of  $\text{CO}_2$  assimilation has been expressed so far in amounts of  $\text{CO}_2$ . In trees the absorbed  $\text{CO}_2$  is reduced to carbohydrates or sugars  $(\text{CH}_2\text{O})_n$ . The assimilation rate expressed in  $\text{CH}_2\text{O}$  can be calculated by multiplying the  $\text{CO}_2$  rate by the ratio of their molecular weights, which is  $30/44$ .

$$F_{ns} = 30/44 * F_{nc} \tag{2}$$

in which:  $F_{ns}$  = Net assimilation ( $\text{Kg CH}_2\text{O ha}^{-1} \text{ yr}^{-1}$ )

So the increase of the  $\text{CH}_2\text{O}$  assimilation rate is  $0.68 \text{ t CH}_2\text{O ha}^{-1} \text{ yr}^{-1}$ . The sugars produced in the assimilation process may be converted into structural plant constituents, stored as reserves or used as a source of energy. The conversion efficiency of sugars into dry matter can be estimated, depending on the biochemical composition of the tissue

(Penning de Vries 1975). In this conversion factor growth respiration is incorporated. The increase into dry matter can be estimated as:

$$\Delta W = E_g * F_{ns} \quad (3)$$

in which:  $\Delta W$  = increase in dry matter ( $\text{Kg ha}^{-1} \text{yr}^{-1}$ )

$E_g$  = conversion factor from sugars to dry matter ( $\text{Kg Kg}^{-1}$ )

Van Heemst (1986) gives conversion factors for agricultural crops ranging from 0.50 to 0.75  $\text{Kg}^{-1}$  dry matter  $\text{Kg}^{-1}$   $\text{CH}_2\text{O}$ . Mohren (1987) calculated the conversion factor for needles, branches, stems and roots of douglas fir separately, varying from 0.6443 for stems to 0.6562 for needles. Using 0.65 as a mean conversion factor in formula 3, the increase in dry matter can be estimated as 0.44 t DM  $\text{ha}^{-1} \text{yr}^{-1}$ . Next, the increase in  $\text{m}^3$  wood can be estimated through the dividing increase in dry matter by the wood density of beech, which is about 700  $\text{Kg m}^{-3}$  (Heilig et al. 1981). Hence the increase is about 0.6  $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ , which is about 5% of the average mean annual increment for beech in the Netherlands (12,8  $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ ; HOSP 1991). This figure match very well with the increase mentioned by Goudriaan and Unsworth (1990), who derived that about 5 to 10% of the actual rate of increase of agricultural productivity worldwide can be ascribed to the fertilizing effect of rising atmospheric  $\text{CO}_2$ .

### 4.3.2 Transpiration

To estimate the effect of such an increase in production on water use, the water use efficiency (WUE) or transpiration coefficient (TC) has to be known as well as the effect of elevating  $\text{CO}_2$  on these coefficients. The WUE usually is expressed in  $\text{g DM Kg}^{-1} \text{H}_2\text{O}$  whereas the TC is expressed as  $\text{Kg H}_2\text{O Kg}^{-1} \text{DM}$ . The TC was estimated by using the transpiration figures from table 1, wood density (Heilig 1981, Laming et al. 1978, van der Meiden 1976) and yield figures from Dutch forest statistics (HOSP 1991). The yield figures represent the saw log part of trees, which is about 75% of the above ground tree biomass (FAO 1993 p. 211). Therefore yield figures of HOSP (1991) have been raised with 25%. The wood density figures given were measured at a moisture content of 12%. Wood density figures have been corrected for this. TC (table 3) was calculated by:

$$\text{TC} = \frac{T * 10^4}{I_b * \rho} \quad (4)$$

in which: TC = transpiration coefficient

T = transpiration ( $\text{mm yr}^{-1}$ )

$10^4$  = factor to convert  $\text{mm yr}^{-1}$  to  $\text{Kg ha}^{-1} \text{yr}^{-1}$

$I_b$  = mean annual above ground biomass increment ( $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ )

$\rho$  = wood density ( $\text{Kg m}^{-3}$ ) at 0% moisture content.

**Table 3 Mean annual above ground biomass increment ( $I_b$ ), Wood density ( $\rho$ ) and Transpiration Coefficient (TC) for seven tree species**

Tree species	$I_b$ ( $m^3 ha^{-1} yr^{-1}$ )	$\rho$ ( $Kg m^{-3}$ )	TC ( $Kg H_2O Kg^{-1} DM$ )	
			estimated	literature
Scots pine	8.5	450	494	300 <sup>1)</sup> , 570 <sup>1)</sup>
Norway spruce	17.0	335	527	107 <sup>3)</sup>
Douglas fir	16.5	405	355	170 <sup>1)</sup> , 127-154 <sup>4)</sup>
Larch	14.6	420	336	
Indigenous oak	8.8	615	528	344 <sup>1)</sup>
Beech	16.1	615	213	170 <sup>1)</sup> , 270 <sup>5)</sup>
Poplar	18.4	310	416	575 <sup>6)</sup>

1) Kramer and Kozwolski 1960  
2) Heinze and Fiedler 1980  
3) Mayer 1984  
4) Mohren 1987  
5) Schulze et al 1986  
6) Hammes 1973

Table 3 shows that the difference in calculated TC between tree species is larger than between the groups of coniferous and deciduous species, for which the mean TC was 428 and 386  $Kg H_2O Kg^{-1} DM$  respectively. Taking into account the accuracy of these calculations and the range in data found in literature (Table 3), we estimated TC at 400-500  $Kg H_2O Kg^{-1} DM$  for all tree species.

In  $CO_2$  enrichment experiments with faba beans, Goudriaan and Bijlsma (1987) found the TC being dependent of the  $CO_2$  concentration. When doubling the  $CO_2$  concentration from 350 to 700 ppmv, the TC showed a decrease of 37% while DM production increased with about 100%. The combined effect of a higher production and a lower TC was a higher total water use of 20 to 30%, depending on the soil water supply. The WUE increased with 56%. An increasing WUE is according with literature (Jarvis 1987, Pastor and Post 1988). Latter reported for some tree species a more than doubled WUE with a doubled  $CO_2$  level, but for most species a smaller response was found. Goudriaan and Unsworth (1990) mentioned a reduction in transpiration rate of 10 to 20% as typical for  $C_3$  plants. In several investigations it was found that canopy evapotranspiration was less or not affected by an elevated  $CO_2$  concentration because the decrease of TC was compensated by an increase in LAI (Goudriaan and Unsworth 1990, Dijkstra et al. 1993).

Now transpiration can be calculated using formulas 5 and 6 successively.

$$\Delta W = \text{forest area} * I_b * \rho \quad (5)$$

in which:  $\Delta W$  = annual increase in dry matter ( $Kg yr^{-1}$ )  
and,

$$T = \Delta W * TC \quad (6)$$

### 4.3.3 Interception

Research on interception has made clear that it largely depends on the intensity of rainfall, tree species and weather conditions (Roestel 1984). Large differences between successive years may occur. This year to year variation can be handled by using long-term average weather data. In literature interception often is given as a percentage of precipitation (e.g. Calder 1977). But since the intensity of precipitation throughout the Rhine basin has a large spatial variability, the percentage of interception may differ significantly per region. Therefore, we estimated the interception on an alternative way.

Coniferous species, except for larch, have needles all the year round. The interception capacity (IC) therefore, remains equal during the year. For deciduous species a distinction must be made between a leaf holding period and a period in which the leaves have been shed. This is of great influence on the IC. The IC have been calculated based on figures of research in the Netherlands. It was assumed that for each tree species the IC is more or less equal throughout the Rhine basin. Large parts of the coniferous forests of the Rhine basin are so called 'dark' needle forests, in which Norway spruce, Silver fir and Douglas fir dominate. Therefore interception characteristics of these species have been used calculating the IC for coniferous forest.

Nonhebel (1987) gives figures for interception as a percentage of annual rainfall (Table 1). Considering that not the whole forest consists of 'dark' coniferous species, an interception of 45% of annual rainfall was used to calculate the IC. Rötter (1994) gives long-term average data for several weather stations in the Netherlands. For these stations mean annual rainfall was 792 mm, distributed over 206 days with rain. Hence the precipitation per rainday was 3.8 mm. With an interception of 45% the IC was 1.7 mm per rainday. For deciduous forest the IC was calculated separately for the summer half year (May-October) and the winter half year (November-April). We used 20% and 10% for the interception in these periods. Long-term average rainfall in summer and winter was 412 mm and 380 mm respectively. Annual number of raindays was 95 and 111 days respectively. Hence rainfall per rainday in summer was 4.3 mm and in winter 3.4 mm. The IC was 0.9 mm and 0.3 mm for summer and winter period respectively, which is 0.6 mm over the year.

The interception capacity can be calculated by:

$$IC_t = IC_r * r \quad (7)$$

in which:  $IC_t$  = total annual interception capacity ( $\text{mm yr}^{-1}$ )  
 $IC_r$  = interception capacity per rainday ( $\text{mm d}^{-1}$ )  
 $r$  = number of raindays per year ( $\text{d yr}^{-1}$ )

Total interception of coniferous forest in the Netherlands was estimated at  $352 \text{ mm yr}^{-1}$ , for deciduous forest at  $119 \text{ mm yr}^{-1}$ . These figures match well with the model results of Nonhebel (1987) as given in table 1.

In table 4 long-term average number of raindays is given for the countries of the Rhine basin.

Pot experiments have proved that LAI may increase with some 20% at doubled CO<sub>2</sub> concentration (e.g. Overdieck 1993). Due to air pollution however, LAI is expected to decrease (Mohren and Bartelink 1987). The combined effect of CO<sub>2</sub> enrichment and air pollution on LAI is still little understood. Annual inventories on the forest condition show a trend of a decreasing vitality (Smits 1992, EC 1993). Since the amount of foliage is the most important factor in the judgement of the vitality, it may be concluded that LAI has not increased over the last decade. Therefore it was assumed that interception will not be influenced due to climatic change.

#### 4.3.4 Total water use

Now the total water use, due to transpiration and interception, can be estimated as:

$$WU = (T + I) * \text{forest area} * 10 \quad (8)$$

in which: WU = total annual water use (m<sup>3</sup> yr<sup>-1</sup>)  
10 = factor to convert mm yr<sup>-1</sup> to m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>

## 5 Possible climate change impacts on forest yield potential and total water use in the Rhine basin

To estimate the range of change in water use of forests in the Rhine basin under elevated ambient CO<sub>2</sub> concentration, three scenarios have been developed. In the first scenario yield is supposed to increase 5% while TC remains equal. Second scenario contains an increase in yield of 5% and a decrease in TC of 20%. Third scenario comprehends an unchanged yield and a decrease in TC of 20%.

The production figures needed were derived from FAO (1993). Because these figures concern only the saw log part of trees, which is about 75% of above ground tree biomass (FAO 1993 p. 211), yield was raised with 25%. Further the production figures were corrected with the result of a Netherlands forest inventory, which showed that the annual yield of the Netherlands forests was about 25% higher than calculated before (HOSP 1991). The areas of forest were taken from volume 4 of this study (Veeneklaas et al. 1994). A mean wood density per country was estimated, taking into account forest composition. For the present TC an average figure of 450 Kg H<sub>2</sub>O Kg<sup>-1</sup> DM was used. All other figures were weighted means (Table 4).

Table 5 shows that current total water use can be estimated at 24.2\*10<sup>9</sup> m<sup>3</sup> yr<sup>-1</sup>. Interception contributes for a larger part to the amount of water use than transpiration. Differences between countries in the ratio of transpiration and interception are mainly caused by differences in forest composition.

In the first scenario total water use was estimated at 24.8\*10<sup>9</sup> m<sup>3</sup> yr<sup>-1</sup>, 2% higher than current water use. The second scenario shows a total water use of 22.6\*10<sup>9</sup> m<sup>3</sup> yr<sup>-1</sup>, 7% lower than at present. Third scenario shows a water use of 22.2\*10<sup>9</sup> m<sup>3</sup> yr<sup>-1</sup>, which is 8% lower than current total water use.

**Table 4 Forest areas, Mean annual above ground biomass increment ( $I_b$ ), Mean wood density ( $\rho$ ), Annual dry matter increment ( $\Delta W$ ) and number of raindays in the countries of the Rhine basin**

Country	Forest area (Mha)			$I_b$ (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	$\rho$ (kg m <sup>-3</sup> )	$\Delta W$ (Tg yr <sup>-1</sup> )	Raindays (n)
	coniferous	deciduous	total				
France	553	298	851	8.3	430	3.1	179
Germany	2216	1568	3783	8.9	440	14.9	185
Netherlands	114	70	204	11.3	480	1.1	206
Luxembourg	42	73	114	12.7	500	0.7	188
Switzerland	693	277	969	8.3	380	3.1	184
<b>Total</b>	<b>3636</b>	<b>2285</b>	<b>5921</b>	<b>8.9</b>	<b>430</b>	<b>22.9</b>	<b>188</b>



**Table 5** Water use of forests in the Rhine basin ( $m^3 yr^{-1} * 10^9$ ) for current and possible future climatological conditions (scenario 1 to 3) and the difference compared to the current water use ( $\Delta$  in percentages)

Country	Current conditions			Scenario					
				1		2		3	
	T	I	WU	WU	$\Delta$	WU	$\Delta$	WU	$\Delta$
France	1.4	2.0	3.4	3.4	+2	3.2	-7	3.1	-8
Germany	6.7	8.7	15.4	15.8	+2	14.3	-7	14.1	-9
Netherlands	0.5	0.6	1.1	1.1	+2	1.0	-8	1.0	-10
Luxembourg	0.3	0.2	0.5	0.6	+3	0.5	-10	0.5	-12
Switzerland	1.4	2.5	3.8	3.9	+2	3.6	-6	3.6	-7
Rhine basin	10.3	14.0	24.2	24.8	+2	22.6	-7	22.2	-8

## 6 Discussion and conclusions

Predictions about change in water use of forests, generated by climate change, contain many uncertainties just like the predictions in climate change itself. Climate change can be divided into a change in ambient CO<sub>2</sub> concentration, temperature, amount and distribution of precipitation (spatial and in time), radiation and so on. These factors may affect plant growth and water use directly as well as indirectly. This study was mainly focused on direct effects such as the CO<sub>2</sub> fertilizing effect and effect of temperature rise on growth and water use of forests. Other processes, such as improvement in initial light use efficiency (Goudriaan et al. 1985) have not been accounted for.

Indirect effects may also be of great importance to net change in growth and water use. Increased crop growth, stimulated by CO<sub>2</sub> elevation, might induce a higher nutrient demand. Goudriaan and de Ruiter (1983) found phosphorus shortage limiting growth almost independently of the CO<sub>2</sub> concentration. Most plants grown at low nitrogen supply rates however, respond as much or more to elevated CO<sub>2</sub> as plants supplied with sufficient nitrogen (Bowes 1993). The response to elevated CO<sub>2</sub> at low nitrogen is the result of an increase in the nitrogen use efficiency in photosynthesis (Arp and Berendse 1993). Higher temperatures may increase decomposition rates. In winter this may enhance leaching because (deciduous) plants have their physiological resting period. Thus it may result in permanent nutrient losses (Rastetter et al. 1991).

Water stress seems to have no or little effect on the growth stimulating effect of CO<sub>2</sub>. A number of studies show a fully maintained effect under water shortage (Gifford 1979, Kimball et al. 1986, Goudriaan and Bijlsma 1987).

Recent studies show that leaf initiation, bud burst, rate of leaf development, leaf senescence, and final leaf size are affected through an elevated ambient CO<sub>2</sub> concentration. Although no significant prove have been found yet, it might be expected that elevated CO<sub>2</sub> may well influence water use through changing phenology and dynamics of leaves, as well as by affecting stomatal conductance (Jarvis 1993). It is also expected that temperature rise affects water use through phenological changes (Cannell et al. 1989). At stand and canopy scale, however, little is known at present about effects of either CO<sub>2</sub> concentration or temperature rise on physiology or structure.

Further, air pollution can be of great influence on growth and water use of forests. In large parts of Europe air pollution affect tree growth (Heij and Schneider 1991). Van der Eerden et al. (1993) found that NO<sub>x</sub>, NH<sub>3</sub> and O<sub>3</sub> reduce the stimulating effect of CO<sub>2</sub>. They estimated that crop loss due to air pollution is about 5%. Mohren and Bartelink (1990) simulated an increasing needle mortality (decreasing LAI) due to air pollution. If simulations started at high initial LAI (7 m<sup>2</sup> m<sup>-2</sup>), predicted yields increased because a decrease in LAI caused less maintenance respiration while light interception decreased only slightly. With low initial LAI (2 m<sup>2</sup> m<sup>-2</sup>) both maintenance respiration and light interception decreased, while yield increased. At this moment the combined effect of rising CO<sub>2</sub> and air pollution on LAI is not clear. Change in LAI is also of importance because it will affect the interception capacity. As shown in table 1 intercep-

tion has a range of 20 to 50% from annual rainfall, depending principally on tree species. With an increasing LAI interception will also increase. It is likely that interception will increase more in forests with low present LAI, e.g. pine forests, than with high LAI e.g. spruce and fir.

Because a lack of knowledge about the combined effect of rising CO<sub>2</sub> and air pollution on tree physiological processes influencing tree growth and water use, it is very uncertain to quantify these effects. Hari et al. (1986) modelled effects of air pollution on forest growth in Finland, taking into account CO<sub>2</sub> effects and fertilizing by nitrate deposition. During the period 1900 to 1980 an increase of 30% in forest growth was found, due to increased CO<sub>2</sub> concentration and N deposition. Continuing changes in the environment were predicted to affect negative changes in forest growth by the end of the 20th century holding on to 2040 and further. The decrease was presumed to be due to acidification effects in the soil. This is confirmed by Morrison (1984) who, in a literature review, concluded that although at present forest growth may seem little diminished, conditions for growth are being altered or processes are being altered in such way that, in the future, growth will be affected.

With all this in mind, a tentative estimated range can be specified, in which a possible change in growth and water use may be expected. Considering that air pollution may reduce the growth stimulating effect of a doubled CO<sub>2</sub> concentration, it may be expected that forest growth will increase 0 to 5%. And further that, due to air pollution, the CO<sub>2</sub> induced decrease in transpiration losses may be less than in a situation without air pollution. The effect of climate change on the water use of forests in the Rhine basin is expected to be in the range of +2 to -8% compared to current water use, with an average change of about -5%.

Results on the water use of forest in this study must be considered as rough estimations. More research, especially model simulations which take spatial variability into account, can give more insight and more exact information. But for such research more spatial data has to be available e.g. on soils, climate, forest composition and productivity.

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## Annex - Input parameters for the computer model MUST

In order to calculate effects of possible climate change on the hydrology of the Rhine basin, RIZA wants to use the computer model MUST (De Laat, 1985). For this model some specific input parameters are needed for forests. In this chapter in short some input parameters and programm modifications are given to specify MUST for forests.

In MUST a distinction is made between deciduous and coniferous forests, therefore different parameters had to be collected for these two forest types.

The program needs 6 input files. In one of them, the definition file (mst.DEF), crop specific parameters can be given.

At first the sink term function can best be set according to values given by Feddes et al. (1988). These are:

PF	ALPHA
0.00	0.00
0.70	0.00
1.00	1.00
2.70	1.00
2.78	1.00
4.20	0.00

Secondly day number and crop hight must be specified. Assuming an average growth rate for deciduous and coniferous tree species of 0.6 and 0.8 m yr<sup>-1</sup>, this can be implemented as:

deciduous forest		coniferous forest	
day (nr)	hight (m)	day (nr)	hight (m)
1.	15.0	1.	17.0
90.	15.0	80.	17.0
170.	15.4	170.	17.6
240.	15.6	240.	17.8
300.	15.6	300.	17.8
367.	15.6	367.	17.8

According to Nonhebel (1987) the capacity of the interception reservoir (SIM) must be specified.

