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Impact of drought and heat on tree and stand vitality – results of the study commissioned by the Federal Ministry of Food, Agriculture and Consumer Protection

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The onset of the so-called “drought study”

The extreme heat and drought of the summer 2003, especially in southern Germany and France attracted public attention. In all land use branches a serious worry arose about the future perspectives of natural production and its climatic bases. In April 2004, the Federal Ministry of Food, Agriculture and Consumer Protection commissioned the Institute for Forest Ecology and Forest Inventory in Eberswalde to conduct a study about the effects of drought and heat on the forests in Germany. First conceptual delibrations led to the assumption that own investigations in the fields of hydroecology and dendroecology are promising and necessary to generate data bases. The hydroecological investigations comprise the cause’s side of the complex relationships between climatic impact, site properties and tree reactions, whereas the dendroecological investigations cover the effects side of these relationships. Time series of yearly growth rates are understood as proxy data of the current tree vigour (Dobbertin 2005). Subject of this contribution are the dendroecological investigations and results.

Material and methods

All investigations were conducted in close cooperation with the forest research institutes of the German federal states (Bundeslaender) at sample plots of the German Intensive Forest Monitoring Program (Level II). This program is a monitoring network of 88 case study sites consisting of typical forest ecosystems in Germany (Fig. 1).

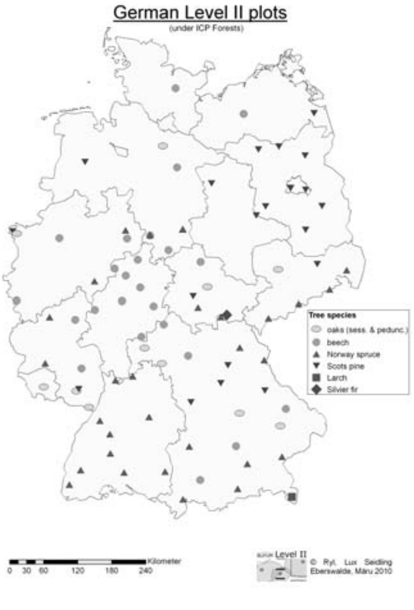

Figure 1: Spatial distribution of the Level II plots in Germany.

At all sample plots, data of water and element fluxes, deposition and climate are recorded as continuous time series. Data about crown condition, phenology and litterfall are collected as yearly values. The amount of growing stand volume is quantified by measuring diameters at breast height (dbh) and heights of all trees every fifth year. More detailed information may be obtained via "http://www.icp-forests.org/MonLvII.htm".

From this situation follows that real yearly growth rates for these Level II plots are not available. As a consequence, own dendroecological sampling and investigations were conducted. In the years 2005-2007, increment cores were taken to build up site chronologies for all German Level II plots. Cores were taken from at least 20 predominant und dominant sample trees of the main tree species (2 cores per tree). The preparation of the samples (drying, fixation, sanding) as well as ring width measurements and synchronization were carried out as following standard procedures. The total numbers of site chronologies per tree species include 33 chronologies for Norway spruce (*Picea abies*), 19 chronologies for Scots pine (*Pinus sylvestris*), 25 chronologies for common beech (*Fagus sylvatica*) and 11 chronologies for oak (*Quercus petrea et robur*), respectively.

The mean site chronology was obtained by application of a special method which ensures the bridging from dendroecology to forest mensuration and forest growth science (Beck, 2008). This procedure consists in the following main steps:

i: determination of the share of the inner part of the stems cross section, which is frequently missed by coring;

ii: derivation of a correction factor to eliminate errors caused by non-optimal boring direction, eccentric position of the pith and shrinkage of the increment cores during drying. The correction factor enables a standardisation of the tree ring widths in a way that the double sum of the corrected ring widths equals the diameter of the stem without bark. By this transformation the proportionality among the ring widths of a series is kept.

iii: Successive cumulation of the ring widths to obtain the course of diameter development; Calculation of the series of relative diameters by standardisation of the absolute diameter series to the final diameter without bark at the time of sampling;

iv: Calculation of series of mean relative diameter and their standard deviation; All series within a band of one standard deviation represent the growth course very well. Growth outliers deviating more than 2 standard deviations from the mean over at least a few decades can be clearly to identified and excluded from further analysis if necessary. In case that individual series are excluded, a recalculation of the mean series and standard deviation bands is necessary.

v: Calculation of the mean absolute diameter without bark at the time of sampling of all included trees. The series of mean absolute diameter growth course is derived by multiplication of the series of the relative dbh with this mean diameter. This mean series contains all information of the mean chronology. The mean ring width series is calculated by the differences of the mean dbh series year by year.

A decision about inclusion or exclusion of values is always based on the entire series and not on annual values. Doing so, the disadvantages of applying the Tukey's biweight robust mean may be avoided (Beck, 2008). Pre-whitening, trend estimation and elimination and indexation may be done in one of the many known ways. However, they have to be applied only once, namely to the mean ring width series. The corresponding parameters of these procedures may be stored, allowing to track the way from dbh via ring width (TRW) to tree ring index (TRI) also backwards: from TRI → TRW → dbh. In other words: The gaps between dendroecology and forest growth science are bridged.

Criteria for the evaluation of growth patterns

Growth trend interruptions and temporary trend deviations

A trend interruption is a sudden change of the average growth rate caused by singular external impacts or by a long-term change of growth conditions. The previous long-term growth trend is interrupted and growth is continues at a different level. Temporary growth deviations occur for a limited duration. The growth rates change more gradually and reverse back to normality in the long run. Temporary growth changes refer to medium term changes of growth conditions.

Disordered relations between first order autocorrelation (AR(1)) and sensitivity in ring width series

Among other parameters, first order autocorrelation AR(1) and sensitivity are used to characterize TRW-chronologies (e.g. Biondi, 1992, 2000; Di Filippo et al. 2007; Dittmar et al. 2003; Fritts, 1976; Piovesan et al. 2008; Wazny & Eckstein, 1991). AR(1) describes the strength of the relation between preceding and current ring widths. This relationship is very close if the growth course shows a clear long-term trend. When a growth course changes rapidly and frequently, autocorrelation drops down. In such cases, sensitivity is significantly inreased. The sensitivity parameter describes the strength of year by year changes within ring width series. Commonly, intense fluctuation of ring width is connected with high sensitivity, low autocorrelation and vice versa. AR(1) as well as sensitivity may be applied to entire time series or to subsections of time series of growth parameters. Combinations of significant autocorrelation and comparatively low sensitivity refer to balanced growth conditions without injurious impacts. In many cases AR(1) and sensitivity fluctuate irregularly within different subsections of a growth time series. This seems to be a normal pattern. A coincidence of a rapid increase of sensitivity exceeding the previous long-term range and a break down of autocorrelation is a strong indicator for stress conditions and harmful external impacts (Beck 2009).

Pointer years

Pointer years can be used to determine the effect of climatic conditions in single years. If the majority of all sampled trees of a stand or of a region show the same direction of growth reactions, the climate has the higher-ranking importance among all growth conditions. The method of pointer year analysis applied here requires a trend estimation by exponential smoothing of the TRW-series and subsequent indexation. The determination of pointer years is done without presetting of tree and stand threshold values. The index values of each tree at time step t, I_t, are transformed into relative growth deviations rGD_t by $rGD_t = 100 \cdot (I_t - 1)$.

The mean relative growth deviation mGD_t of all trees of the chronology and the corresponding standard deviation sGD_t is calculated for all time steps of the series. A year is decided to be a pointer year if $(mGD_t - sGD_t) \cdot (mGD_t + sGD_t) > 0$.

Growth reactions caused by the summer 2003

The course of the weather conditions during the summer of 2003 was the cause for conducting this study. Questions of special interest are the extent of immediate growth reductions in 2003 and the duration and the extent of the aftereffects on the growth course in the following years. To ensure a proximate comparability of growth reactions of various trees and stands, the absolute ring width values were transformed into relative ring widths with reference to the preceding five-year period 1998-2002

Climate – growth relationships

The existing tools to analyse relationships between climate and tree growth rates are based upon monthly values of climatic parameters (response functions according to Fritts 1976; state-space models by Visser and Molenaar 1988; bootstrapped response functions by Guiot 1991; evolutionary and moving intervals by Biondi 1997, Biondi & Waikul 2002). However, the climatic elements form a continuous series with seasonal properties without any monthly bounds. Within this continuous climatic series, those intra-annual time spans have to be found which are most closely related to the course and rhythm of tree growth.The method chosen consists in floating intra-annual time spans of variable width to find the best regression approach for describing climate–growth relationships (Beck 2007). The method performs an objectified variable selection based on daily data of temperature and precipitation. The technical implementation of these methods consists in the analysis tool CLIMTREG (climatic impact on tree growth). The newest release of this software may be obtained from the author.

Results

Indicators of disturbances

Growth trend interruptions, temporary trend deviations and disordered AR(1)-sensitivity relations were used jointly as diagnostic criteria to evaluate the normality or the size of disturbances in growth series. The assessment of the occurrence of disturbances was done by use of the mean radial increment and mean basal area increment series (Beck 2009). The share of disturbed growth courses related to the total number of chronologies per tree species was calculated (Fig. 2).

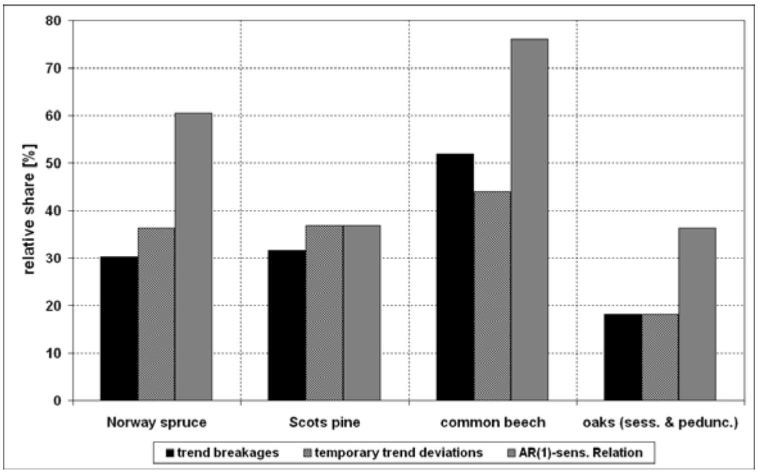

Figure 2: Frequency of the occurrence of disturbance indicators

Pointer years

Pointer year analysis was carried out for each site chronology, for peculiar regions of Germany and for the four main tree species as supra-regional, nationwide pointer years. The nationwide analysis included 650 spruces, 686 pines, 554 beeches and 209 sessile and pedunculate oaks within the common overlap interval from 1945 to 2006 (Fig. 3).

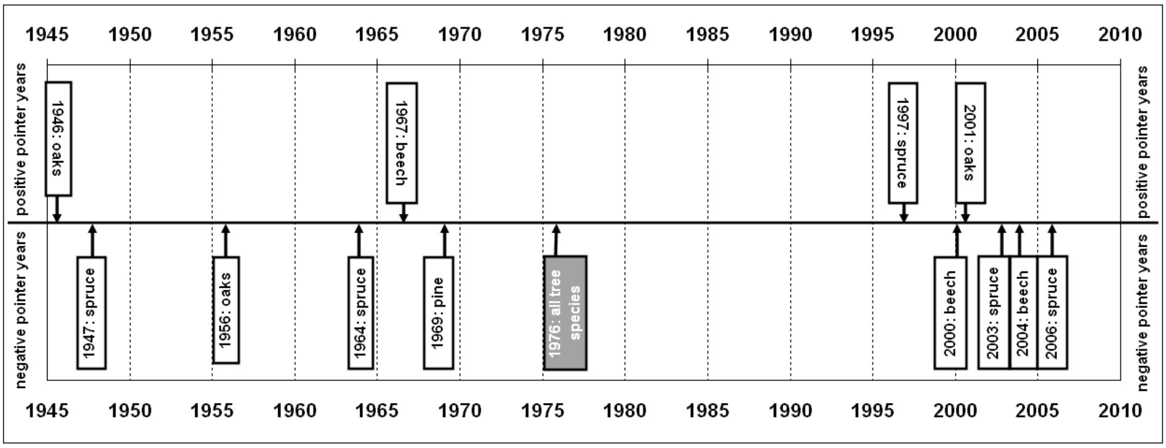

Figure 3: Nationwide negative and positive pointer years of the four main tree species in Germany. Growth reactions in the years from 2003-2006 are related to the reference period from 1998 to 2002.

The variations of mean relative ring width between 1998 and the year of sampling of all Level II plots of a tree species are displayed as cohorts of curves (Figure 4a-d).

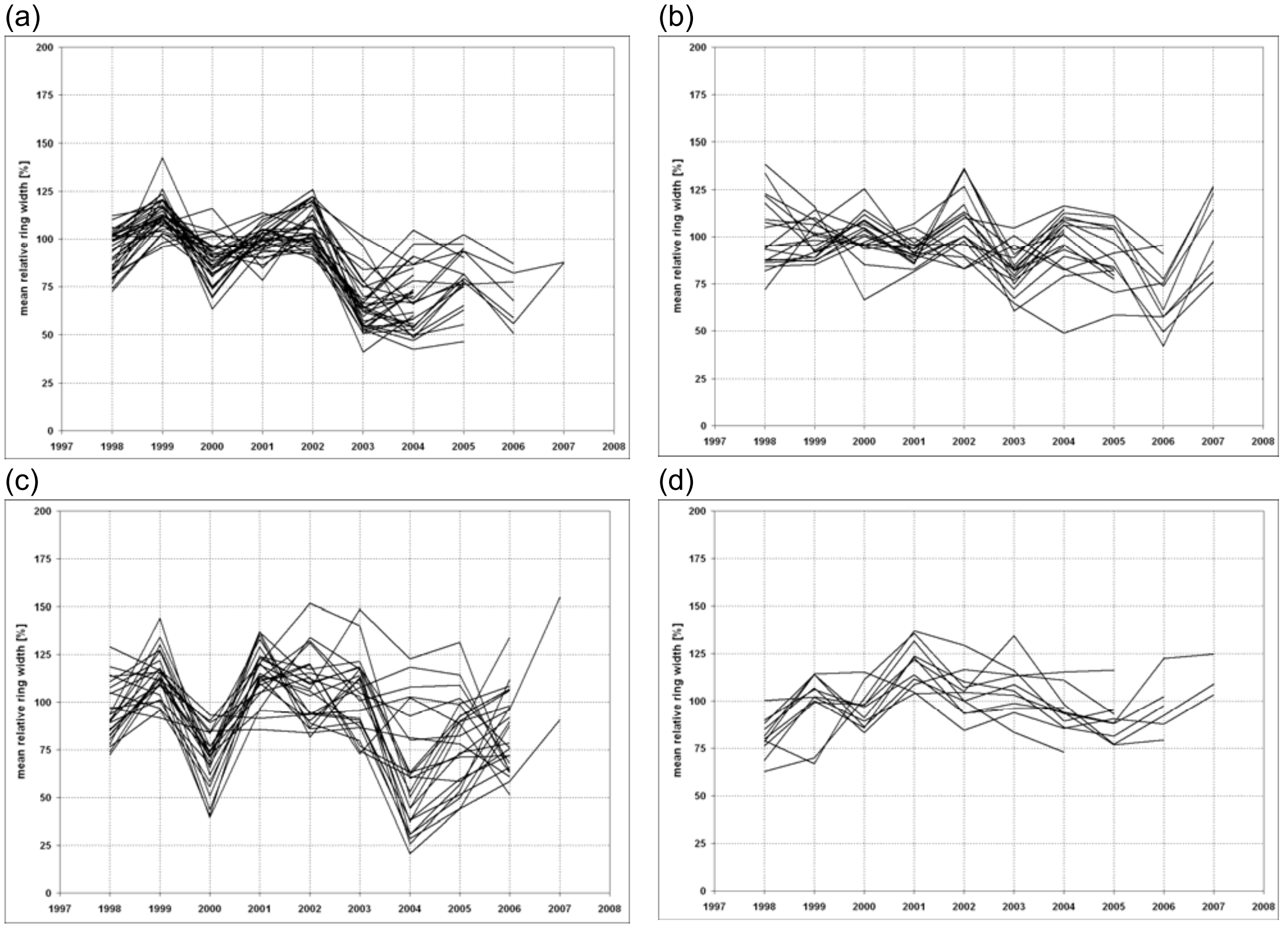

Figure 4: Relative mean ring width variations after 1998 of cohorts of (a) Norway spruce, (b) Scots pine, (c) common beech, and (d) sessile and pendunculate oaks over all Level II plots over Germany.

Climate–growth relationships

The results of the investigations of the effects of climatic impacts on tree growth rates by application of the analysis tool CLIMTREG are manifold, according to the differentiation of the local climate within Germany, the tree species and the site properties. As an illustrative example, the analyses of 9 beech chronologies from central Germany (Hessen) were summarized (Fig. 5a-b). Current growth rates are predetermined by weather conditions of the preceding summer and autumn to a considerable extent. The influence of precipitation exceeds that of temperature.

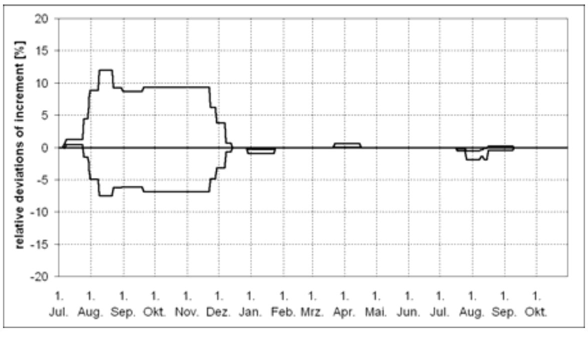

Figure 5a: Efficacy of the intra-annual temperature on the growth rate of common beech.

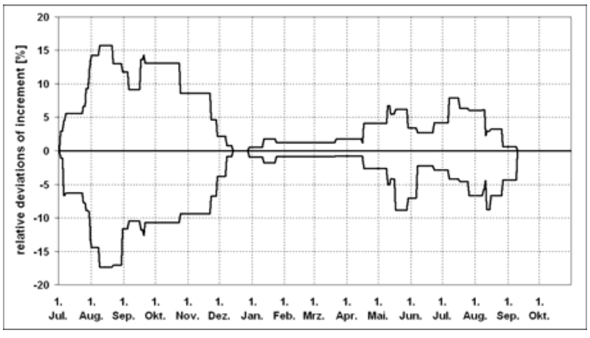

Figure 5b: Efficacy of the intra-annual precipitation on the growth rate of common beech.

This pattern of climatic efficacy is typical for sites where temperature is a not a growth-limiting climatic factor, different from the high-elevation or polar timberline.

Discussion

Disturbances within growth histories of trees as they appear as trend interruptions, temporary growth deviations and disordered AR(1)-sensitivity relations hint at an at least temporarily reduced vitality. Generally, increasing deposition of noxal and eutrophic substances up to a peak in the 1980s followed by more frequent extreme climatic impacts nowadays is considered as cause of such disturbances. However, the limits of buffering ability against external forces such as climatic impacts are still unknown. It has to be emphasised that all criteria for disturbances were found at living trees, which appeared physically undamaged at the moment of sampling. Nevertheless, considerable species-specific differences concerning the frequency of disturbances can be observed. Beech and spruce are more frequently affected than pine and oak.

Exceptional harmful or favourable climatic courses leave their marks as supra-regional negative or positive pointer years in tree ring series. The analysis of these pointer years of the four main tree species showed that there are more negative than positive pointer years. Harmful climatic impacts cause a uniform reaction of the majority of sample trees by withdrawal of resources or by exceedance of physiological thresholds. The recreation process, however, is less uniform among the individual trees. The appearance of pointer years is species-specific. Common pointer years of different tree species are extremely rare. The important exception is the year 1976 in which all main tree species were affected. A cold late winter and spring was followed by a hot and dry summer. Neither was the cold winter the coldest nor was the summer drought the driest among the extreme weather events, but the serial appearance of two harmful climatic impacts within one year resulted in an outstanding negative pointer year of the main tree species across most parts of Central Europe. After 1976, for a time span of 20 years, not a single pointer year occurred. Probably, other external forces superposed the effects of climate. Beginning with the year 2000 nationwide pointer years returned with a fast sequence of negative pointer years of beeches and spruces in 2000, 2003, 2004 and 2006.

The summer heat and drought in 2003 affected the tree species in a different manner. This concerns the intensity of the impact on the growth rate of 2003 as well as the duration of the aftereffects (Figure 4a-d). Norway spruce, which is the main tree species in Germany, was most harmfully affected by the deepest growth depression in 2003 and by the most enduring aftereffects. The growth courses of the investigated spruce stands show a very slow progress of recreation. Common beech, which is the most important broadleaved tree species in Germany, is affected by very sensitive growth depressions as well, but mostly with a delay of one year. However, the recreation progress is much faster than in that of Norway spruce. The pines react to the 2003 drought with prompt growth reductions but also with a fast recreation. Generally, pines exhibit a high degree of reactive elasticity or with other words, resilience. Sessile and pedunculate oaks tend to weak and inertial growth reactions. Seemingly, oaks dispose of a high degree of stress tolerance.

Quantified climate-growth relations for Norway spruce forests indicate a significant influence of climate on growth rates during summer and autumn of the previous year. In the German low mountain ranges, a continuous precipitation supply during the previous year as well as during summer of the current year is of greater importance than in mountainous south-western Germany, where precipitation is generally higher. In contrast to Norway spruce, climate during the current vegetation is of greater importance for Scots pine. In the dryer north eastern German lowlands, continuous precipitation supply from autumn of the previous year to the summer of the current year is of higher importance than in southern Germany. Similar to spruce, beech responds more strongly to climatic conditions of the previous than during the current year. In Hessen, which is the centre of the German beech distribution, a continuous precipitation supply up to the late summer of the current year is of higher importance than in western Germany.

Conclusions

Climate-growth relationships are modified by region, tree species and site properties The differences of growth reductions induced by the drought of 2003 are caused by the regionally different intensity of drought as well as by the different soil properties (water holding capacity) and additionally by the kind of adaptation of the tree stand to these site properties.

The shade tolerant tree species spruce and beech with higher requirements to soil and air humidity suffer more from drought events than pines and oaks. Especially, artificial spruce forests outside of their natural montane distribution range are highly endangered by drought and the subsequent attacks by bark beetles.

Up to the 1970s, winter coldness is a main cause of negative pointer years. During the last 20 years negative pointer years are mainly associated with summer heat and drought. Forestry and silviculture are confronted with changing climatic conditions for forest growth. The choice of tree species aiming at forest conversion measures should be decided very carefully, especially under conditions of limited precipitation supply. Results of dendroecological investigations comprising a number of regions, tree species and site properties are suitable to support forest decision making.

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