not affect the studies. Nevertheless, the treatments carried out before the measurements are difficult to define afterwards.

Semitemporary data remeasured at fixed intervals may be a suitable compromise for most occasions. However, the remeasurements should cover a sufficient period in order to include the whole range of variation due to weather conditions. It is also important to cover the extreme densities and treatments in the data. The remeasurement intervals also need to be long enough to ensure that growth can be detected from noise introduced by measurement errors.

Final Remarks

Forest simulators have been developed from simple standwise yield tables and models to increasingly complex single-tree models. The new models are more flexible and suitable for many applications, for mixed stands and even for changing management practices. The causal relationships governing the growth of forests are easier to account for in single-tree models than is a stand model. However, the accuracy of the predictions has not been improved likewise. On the contrary, the more complex a simulator is, the more uncertain the predictions may be.

All in all, it is important to study the contribution of different sources of uncertainty (i.e., to formulate error budgets) to concentrate research efforts where they are most needed. It may well be that the main source of uncertainty is not the growth simulator at all, but the quality of initial data, for example. It would also be useful to separate the inherent randomness of growth from pure ignorance.

See also: **Experimental Methods and Analysis**: Statistical Methods (Mathematics and Computers). **Inventory**: Modeling. **Mensuration**: Forest Measurements; Growth and Yield

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Tree-Ring Analysis

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Introduction

Tree-ring analysis or dendrochronology is both an old and a modern science. Just counting tree rings sounds simple, but in the context of forest dynamics tree age is an important and valuable parameter. The pattern of tree-ring width, wood density, element content, and other features store information on past growth conditions. Biomonitoring is the reflection of growth factors by biological organisms and their change in time. Tree-ring analysis extends the monitoring period considerably into the past and could be considered as retrospective biomonitoring.

For a long time dendrochronology (from Greek: dendros, tree; chronos, time, and logos, science) was associated with the dating of old houses, paintings, and archaeological samples. In recent decades however it has become a science with a broad range of applications such as global climate change, canopy process decline, the carbon cycle, and many others. Due to its manifold applications for other branches of science dendrochronology is sometimes considered as just a tool for archaeology, art history, biology, climatology, forestry, glaciology, etc. The development of techniques like X-ray densitometry, isotope analysis, special statistical analysis for tree ring interpretation, etc., together with new aspects in the theory of tree-ring formation mean that tree-ring analysis should be considered as an independent branch of earth science.

History of Dendrochronology

Leonardo da Vinci, who in the sixteenth century realized the relation between climate and widths of tree rings, is considered the father of dendrochronology. The beginning of broad scientific knowledge of wood formation, tree rings and climate, however, can be dated to the middle of the nineteenth century, when Theodor Hartig and others postulated their theory of tree-ring formation as a consequence of low temperature in winter. Additional milestones reflect the progress in dendrochronology during the last 150 years.

- 1927: Ch. Coster, a Dutch forester, proved the existence of annual tree rings in the tropics for many species on Java and explained the climatic background.
- 1935: First age dating of a wood sample by cross-dating the tree ring patterns of a construction beam by A. E. Douglass (Pueblo Bonito).
- 1954: E. Schulmann found the oldest living tree in the white mountains of California (bristlecone pine (*Pinus longaeva*): 4798 years).
- 1976: Hal C. Fritts introduced statistical methods to analyze climate signals in tree ring sequences as the base for climate reconstruction using tree rings.
- 1983: Fritz H. Schweingruber established modern dendro-ecology and developed X-ray densitometry.
- 1993: B. Becker developed the longest oak chronology with 11 800 years of tree rings in southern Germany.

Wood Anatomy and the Ecological Background of Tree-Ring Analysis

It is still widely assumed that tree rings occur only in the temperate and boreal zones. The gradual deceleration of growth until cambial dormancy as a consequence of low temperature results in the formation of latewood, which differs structurally from the earlywood of the previous growing season.

In general three different types of climatic seasonality affect annual tree growth (**Figure 1**):

1. Variation of annual temperature with temperature near or below the freezing point in winter.
2. Annual flooding of the great river systems in the tropics (e.g., the River Amazon) rising up to 5 m above the forest floor for 6 or more months per year causes anoxic conditions in the soil. Root respiration and water uptake is hindered; many species shed their leaves and have a cambial dormancy. This is reflected by annual rings in the wood.
3. Variation of precipitation between rainy season and dry season. This climate type covers the major part of the tropics.

Tree rings are bound to the process of secondary radial growth of the xylem. This is the case in gymnosperms and dicotyledonous angiosperms. Woody monocotyledons never form tree rings due to the absence of secondary xylem. In general, growth zones can be classified into four basic anatomical types according to the features at the ring boundaries (**Figure 2**). Many species combine several of the four growth zone features.

Type 1

Density variations occurring in gymnosperms as a unique feature and in broadleaved trees together with one or more of the following features: cell wall thickness becomes greater and the cell lumen becomes smaller from earlywood to latewood (all coniferous species, Annonaceae, Verbenaceae, Lauraceae, and many other families).

Type 2

Marginal parenchyma bands run around the entire cross-section and consist usually of one or few cell rows (Annonaceae, Bignoniaceae, Leguminosae, Meliaceae).

Type 3

This is the tissue pattern type. The most complicated and frequently misinterpreted structure is to be found in Euphorbiaceae, Moraceae, Sapotaceae,

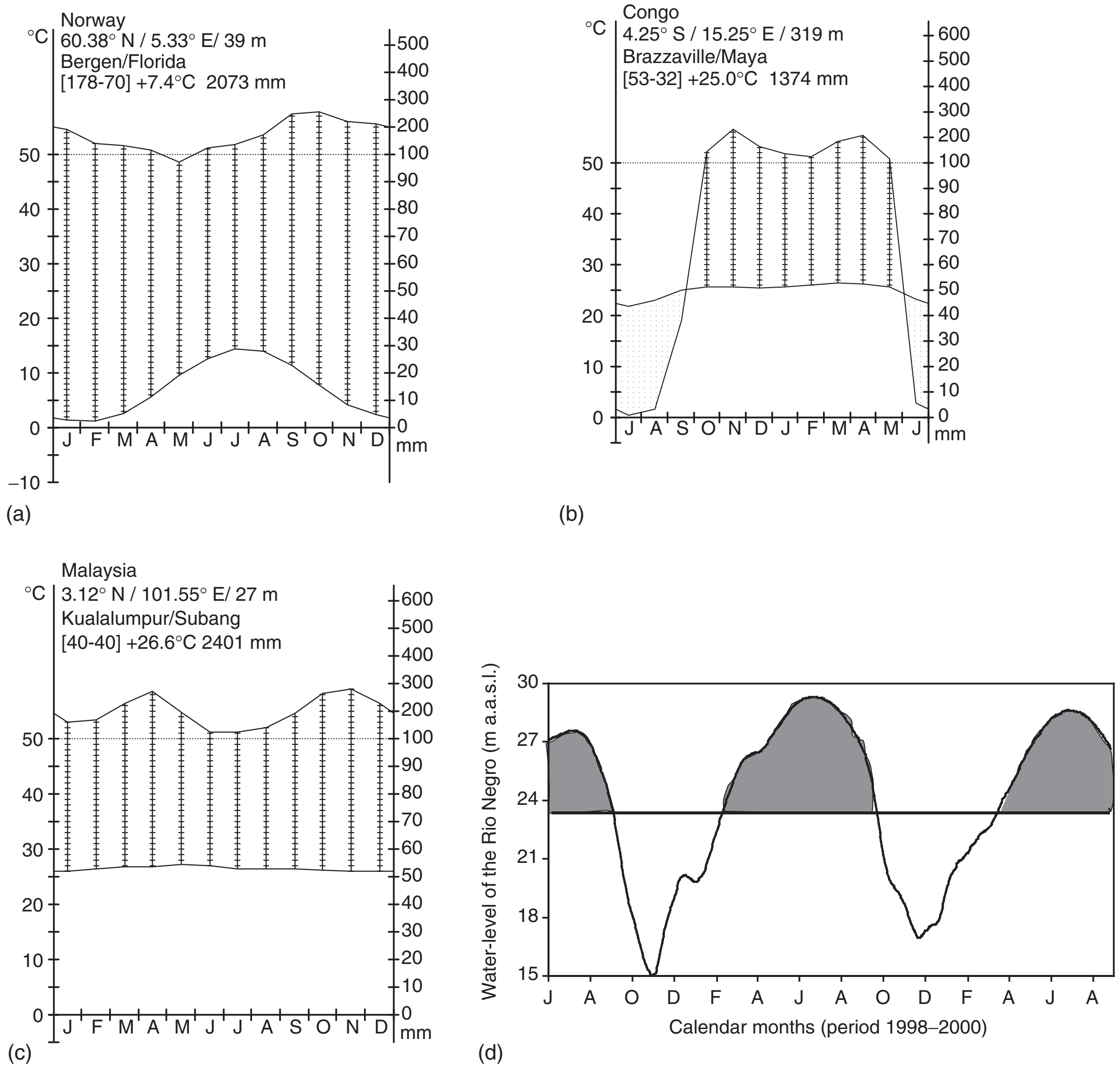

Figure 1 Typical climate diagrams from (a) the temperate zone, the tropics ((b) seasonal and (c) everwet), and (d) the flooding regime of the Amazon river. Seasonality is expressed in high latitudes through temperature variation, in low latitudes through variation in precipitation in the course of the year.

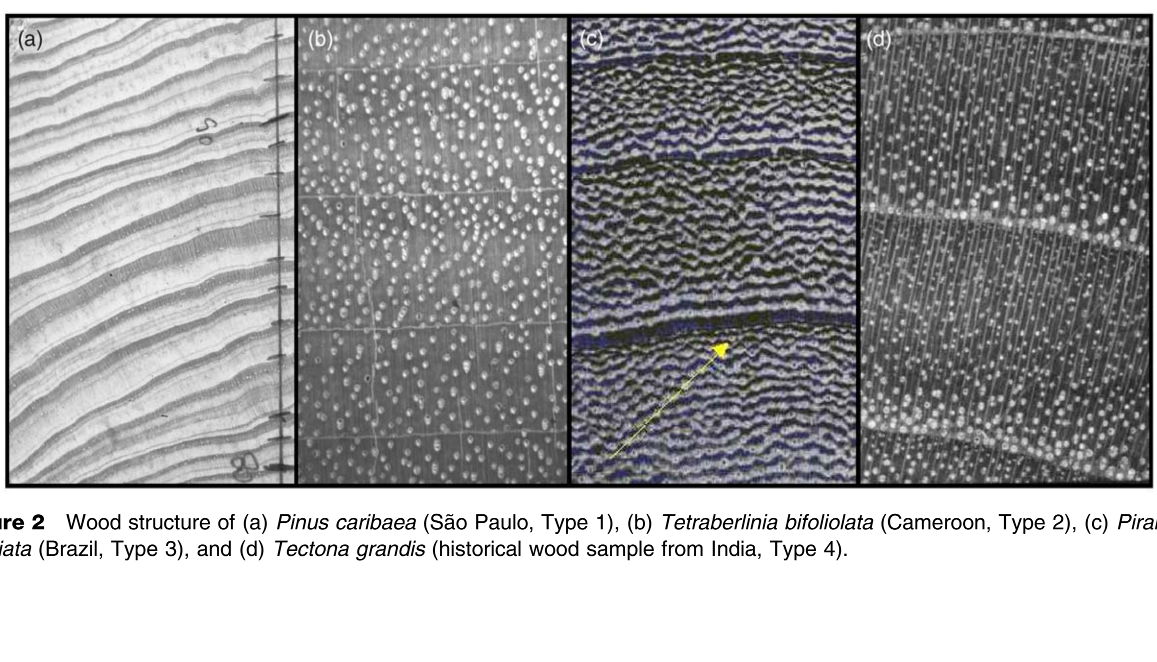

Figure 2 Wood structure of (a) *Pinus caribaea* (São Paulo, Type 1), (b) *Tetraberlinia bifoliolata* (Cameroon, Type 2), (c) *Piranhea trifoliata* (Brazil, Type 3), and (d) *Tectona grandis* (historical wood sample from India, Type 4).

Bignoniaceae, in *Ulmus* spp., *Fraxinus* spp., and many others. Rings are characterized by periodical patterns of parenchyma and fiber tissue. The bands usually become narrower towards the end of a growth zone.

Type 4

This type has vessel distribution in the growth zone. Ring porousness is widely distributed in the temperate zones (e.g., *Quercus*) but occurs in only a few examples in the tropics (e.g., *Tectona grandis*, and some Meliaceae).

Basic Principles of Dendrochronology

One of the most important dendrochronological techniques is the comparison of tree-ring time series of different trees. This is based on ecological principles.

Variation of Tree-Ring Features from Year to Year Based on the Influence of Growth Factors, Mainly on Climate Variations

This is a specification of the ecological rule of limiting factors, especially temperature, radiation, and precipitation which vary from one year to the other. This variation is the reason for the existence of unique tree-ring patterns and makes possible the identification of certain growth time periods. Site conditions influence the intensity of reaction to these factors. Sensitive species usually show great variations in ring width from one year to the other while complacent trees react little.

Since the Climate Influences All Trees on a Given Stand Equally, Tree-Ring Patterns Are Similar between Individuals of a Stand

The degree of similarity depends on the distance between growing sites, the climatic variability in a region and the ecological range of a tree species. As an example oak tree-ring chronologies from sites in the flat plains of northern Central Europe have a high degree of similarity and are even comparable with chronologies from Ireland, both being influenced by an oceanic climate type. Chronologies from spruce (*Picea* spp.), however, may differ over a short distance when the trees grow at different elevations.

Every Ring Can Be Dated to a Certain Growing Period or to a Calendar Year

Tree-ring patterns are the mirror of the growth conditions of a tree. The rings and their features represent an archive of growth conditions during a tree's life.

Methods

Sample Collection and Preparation

One advantage of dendrochronological investigations is the low impact on the living tree when samples are taken with an increment corer. For yield estimations stem disks are chosen from breast height. In dendrochronologically unknown or seldom used species it is helpful to start with the investigation of a cross-section. The structure of the growth zones and the occurrence of matching and wedging rings can be more easily identified on a stem disk than on a small core beam.

The core samples must be glued in wooden supports. Careful preparation of the sample surface is essential for a successful analysis. This can be carried out by polishing the sample with sandpaper of increasing gradation.

Data Measurements

Douglass built chronologies to date the Pueblo Bonito group by estimating and classifying the ring widths in three classes ('skeleton plots'). This method is based on the concept of 'pointer years,' which are substantially smaller or wider than the neighboring rings (**Figure 3**). This system was further developed by Schweingruber and extended to 'abrupt growth changes' (**Figure 4**). In most cases ring widths will be measured by means of a typical measuring device usually with a precision to the nearest 0.01 mm.

Besides ring width several additional features of tree rings were tested in the past for climatological or ecological signals. One of the most important is wood density. A thin sample is irradiated with X-rays, thus developing an image of its density on a film. A densitometer measures the darkness of the film indicating the variations in density (**Figure 5**). The results provide several kinds of information. It is obvious that the latewood of coniferous trees from high elevations and high latitudes carries a strong

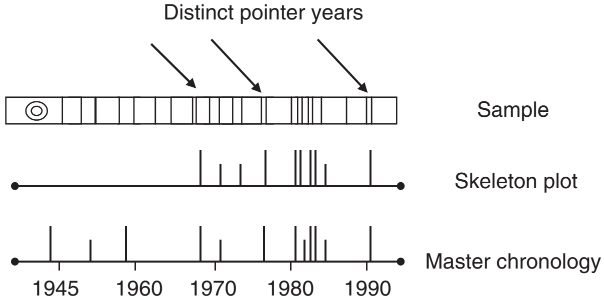

Figure 3 Translation of ring width variation into a skeleton plot and the comparison with a master chronology (below). Small rings are indicated by a bar of different length corresponding to the intensity of growth reduction.

climate signal, i.e., the temperature of the late summer. Recently image analysis has played an increasing role in dendrochronology in the search for additional relevant signals of climate. Time series of tree-ring features such as vessel size and vessel area may help to clarify the relation between tree growth and rainfall patterns (**Figure 6**).

The content of chemical elements and isotopes in tree rings has been tested in different situations. The best results can be expected from elements and isotopes which are bound to the cell wall structure. Some other elements tend to be mobile within the stem. The content of these elements can serve for the detection of environmental stress. Stable isotopes, especially those which are part of the cellulose molecule (D, ^{13}C, ^{18}O) have recently been used to test for climatological signals.

Radioactive isotopes, especially radiocarbon, play an important role in dendrochronology. The analysis of exactly dated oak and bristlecone pine wood samples have served to calibrate the radiocarbon concentration curve for the past 12 000 years. This was necessary since the concentration of CO_2 in the atmosphere has varied considerably in the past and one radiocarbon date could be linked to more than one calendar age (**Figure 7**). The calibration was the precondition for a much higher precision of radiocarbon dating of archaeological samples. Furthermore ^{14}C estimations can be used to test the existence of annual rings in tropical trees. Based on the atomic weapon effect (the ^{14}C content in the atmosphere almost doubled between 1950 and 1964 because of 404 atomic bomb explosions in the atmosphere) single isolated growth zones can be dated by comparing their radiocarbon content with that of the atmosphere (**Figure 8**).

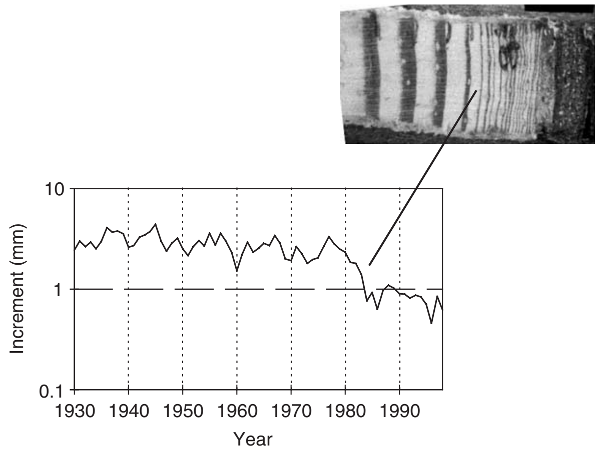

Figure 4 Example of an abrupt growth reduction in Scots pine (*Pinus sylvestris*) and the corresponding ring curve.

Cross-Dating of Ring Curves

The second principle of dendrochronology, the comparison of tree-ring patterns of different individuals, requires tools and limits for matching ring curves. Typical statistical methods are correlation, Student's *t*-test, which combines correlation and length of the compared time series, and the

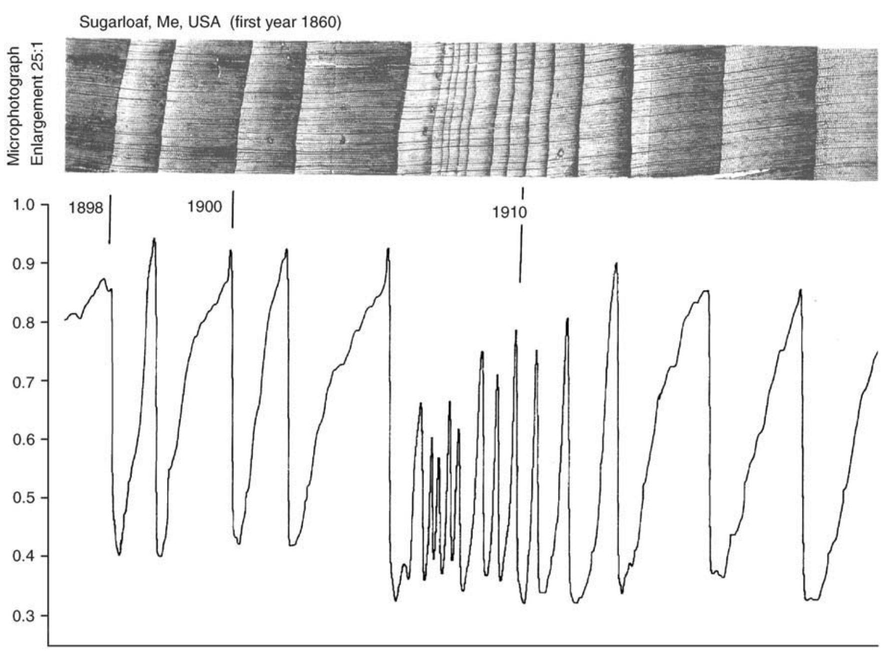

Figure 5 Microsection and corresponding densitogram of pine (*Pinus sylvestris*) derived from X-ray densitometry. Note the variation within one ring and also year by year. 1951 has a considerably lower maximum density than the previous year.

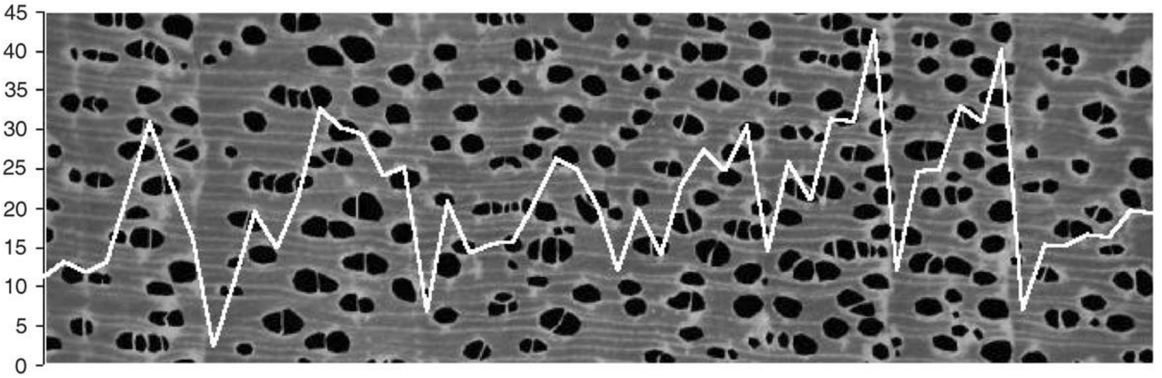

Figure 6 Image analysis of *Terminalia sericea*. In the digitized photograph different features like the vessels can be highlighted, and their dimensions will be measured automatically. The line shows the intra-annual change of vessel area as a percentage of the entire cross-section.

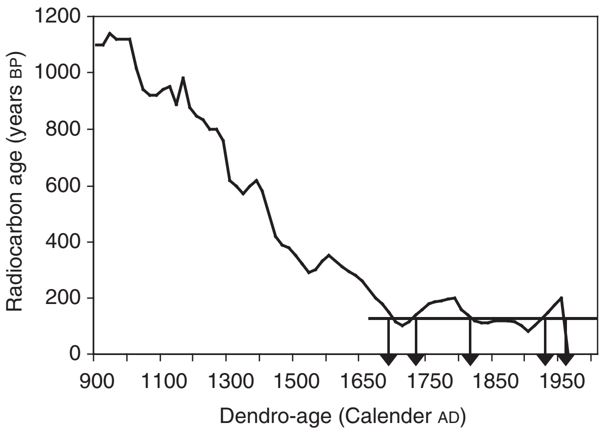

Figure 7 Calibration curve for radiocarbon values to (real) dendro-ages. The curve is derived by analysing tree rings from exactly dated bristlecone pine and European oak. It shows the fluctuation of past ^{14}C content in the atmosphere. The variations between 1650 and 1950 impede the age dating of wood samples from this period, since one radiocarbon age has several possible dendro-ages.

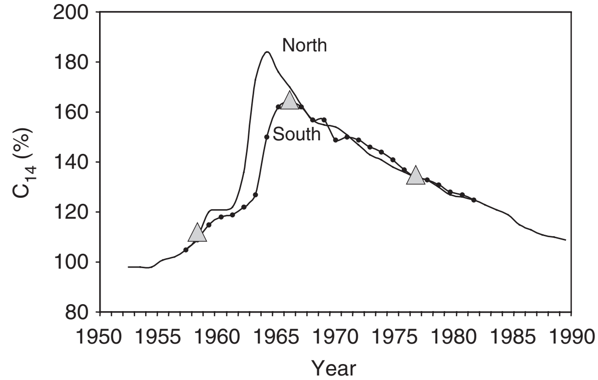

Figure 8 Radiocarbon content of the atmosphere in the northern and the southern hemispheres since 1952. In 1963 the test ban treaty stopped the majority of atmospheric atomic bomb explosions. The ^{14}C content in the atmosphere has declined continuously from that time. The variation makes possible the exact age dating of individual growth zone using two or three samples on different angles of the curve as it is indicated by the triangles.

'Gleichläufigkeit.' The latter means the percentage of parallel trend changes (**Figure 9**). Only those individual curves that match other curves can be included in the chronology.

Data Processing and Transformation

Tree-ring sequences and patterns store various information including the age of the tree, short-term climatic oscillation, and long-term trends. Year by year variation can be traced back to climate variability, but other biotic factors (e.g., pests) or abiotic factors (e.g., air pollution damage by storms, or severe floods) also may cause abrupt growth changes from one year to the next (**Figure 10**). Long-term trends in tree-ring curves can be traced back to long-term environmental changes, mainly processes

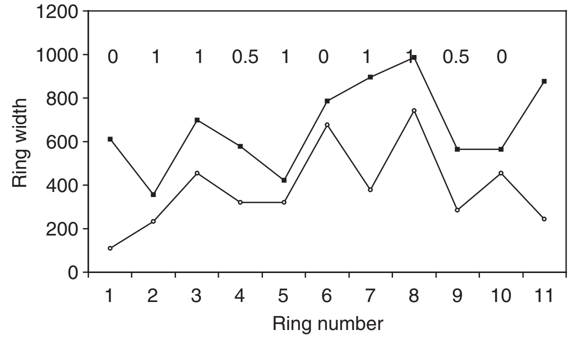

Figure 9 'Gleichläufigkeit' is an important measure for the similarity of tree-ring curves from different trees. It measures the concurring number of trend changes from one year to another. In this example every parallel trend change counts 1. When one curve does not change its direction the value 0.5 is given. The calculated Gleichläufigkeit is 60%.

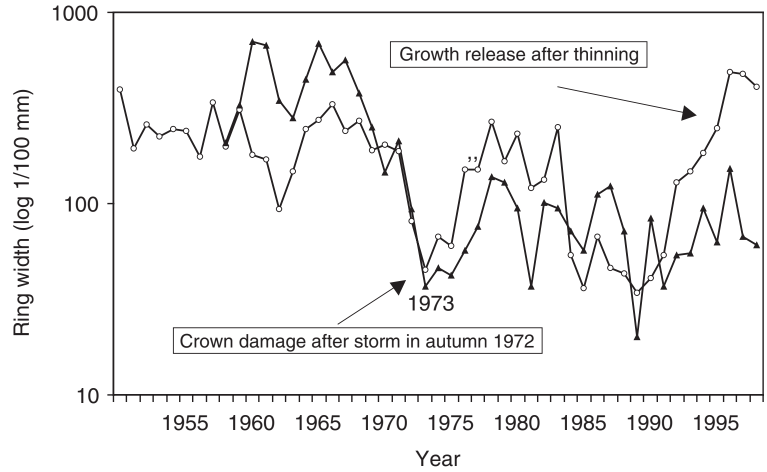

Figure 10 Tree-ring curves of trees exposed to crown damage after a catastrophic storm. One tree released after a couple of years, the other remained on a very low increment level. Note that the scale on the *y*-axis is logarithmic. This presentation points to the minima of a curve and helps to identify 'pointer years.'

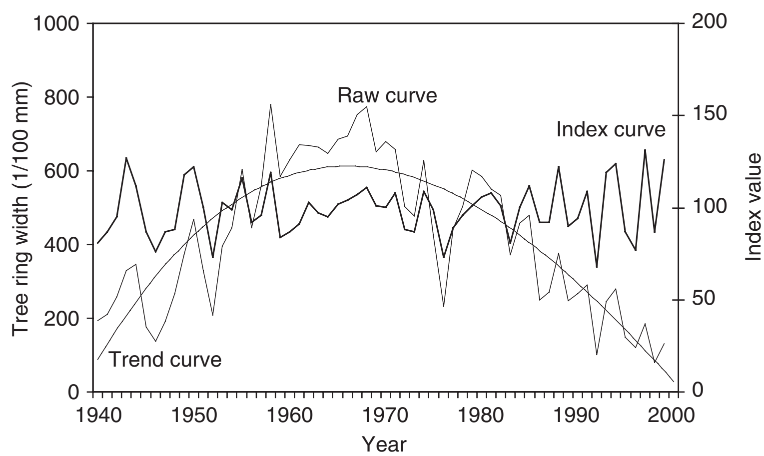

Figure 11 Detrending of an original raw ring curve. For the raw curve a trend is calculated, so that different smoothing functions are possible. The individual raw data and the related data points of the end curve were divided by each other. The resulting residuals form the detrended index curve.

such as increased competition or sudden loss of competition when gaps are opened through tree fall or human activities.

The influence of climate on tree growth can be shown by statistical analyses of tree-ring time series. After cross-dating the calculated mean curve must be detrended to differentiate between short-term oscillation and long-term trend. This procedure is called indexing and starts with the calculation of a trend curve. Various algorithms may be used such as Hugershof or moving average (**Figure 11**). The detrended curve consists of the residuals of raw curve values divided by the values of the trend curve. The residuals vary around a mean and show a normal distribution, a precondition for the calculation of a correlation with climate data.

Applications

Old Trees and Long Chronologies

The maximum age of a tree species is genetically fixed to a certain degree. The oldest living being is a bristlecone pine (*Pinus longaeva*) in the White Mountains in Arizona, USA at 4767 years. *Pinus longaeva* and *P. aristata* grow very slowly due to poor site conditions at the timberline at 3400 m with precipitation of about 100 mm per year. *Fitzroya cupressoides* (3600 years) and *Sequoia sempervirens* (2200 years) reach their ages at lower elevations and higher precipitation. All these species with a longevity over 1000 years are gymnosperms. Angiosperm trees are always much younger. The oldest dendrochronological confirmed ages are known from

Quercus spp. in North America and northern Europe (600–700 years) and for *Weinmannia trichosperma*, an emergent broadleaf tree from Chile (about 730 years). For tropical trees only a few dendrochronological confirmed ages have been published. The oldest trees are *Hymenolobium mesoamericanum* in a Costa Rican forest and *Piranhea trifoliata* from the Amazonian floodplain forests, with ages of between 550 and 600 years, respectively.

A driving force of dendrochronological progress is the construction of ever longer chronologies. Their construction starts with coring living trees to construct a first master chronology. This will be extended to the past by additional samples from already felled and old timber. This is possible when the innermost part of the recent sample shows overlapping parts with the outermost part of old samples. Both parts can be cross-dated and linked (**Figure 12**). In some cases beams of a location can not be dated immediately. Then a floating chronology will be build and dated preliminary by means of radiocarbon analysis. Later the floating and the master chronology might be connected with a 'missing link.'

The longest times series, consisting of thousands of individual samples is the 11 800 years long chronology of oak from southern Germany. A longer chronology is under construction for *Pinus sylvestris* stems, which have been found in alluvial sediments in the southern French Alps. Additional chronologies from other parts of the world are listed in **Table 1**.

Dating of Buildings, Works of Art, and Archaeological Samples

The existence of described chronologies has made possible substantial progress in many historical scientific applications, such as archaeology and the history of art and of buildings.

Many paintings in the late sixteenth and the seventeenth century were made on oak panels; these can be dated and differentiated from later copies. Expensive violins, e.g., from Stradivari, have also been tested for their originality. In some cases the wood of violins labeled from the beginning of the eighteenth century has proved to have been cut in the late nineteenth century, about 100 years after Stradivari's death (**Figure 13**).

Table 1 Chronologies with long timespans and their origin

Species	*Timespan (years* BP*)*	*Location*
Quercus spp. (oak)	11 800	Southern Germany
Pinus longaeva (bristlecone pine)	8 400	Arizona, USA
Pinus sylvestris (Scots pine)	7 500	Finnish Lapland
Picea, Larix spp. (spruce, larch)	6 000	Alps
Lagarostrobos franklinii (Huon pine)	4 000	Tasmania, Australia
Larix sibirica (Siberian larch)	4 000	Western Siberia
Fitzroya cupressoides (alerce)	3 600	Southern Chile
Tectona grandis (teak)	415	Java

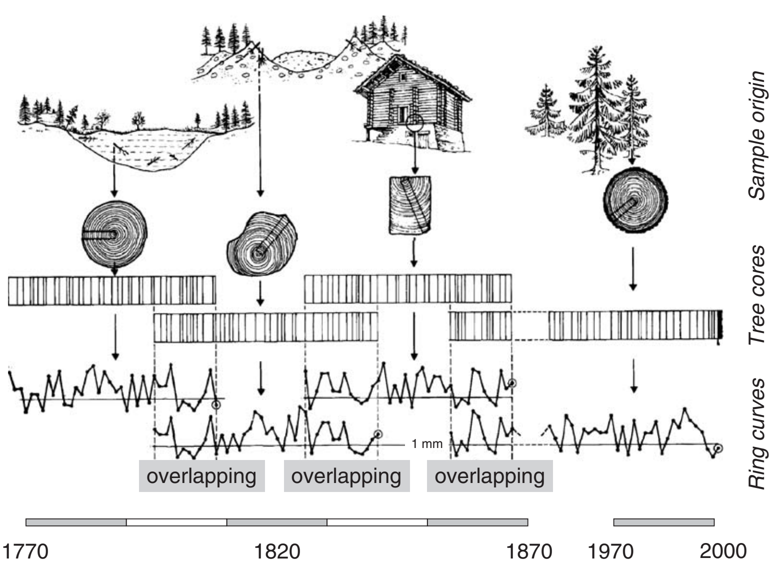

Figure 12 Scheme of the construction of a tree-ring chronology starting with samples from a living tree (right-hand side) and then including stepwise construction wood and subfossil samples. The diagram shows the ring-width patterns of the samples, their transformation into curves, and the overlapping sequences which match the individual curves together.

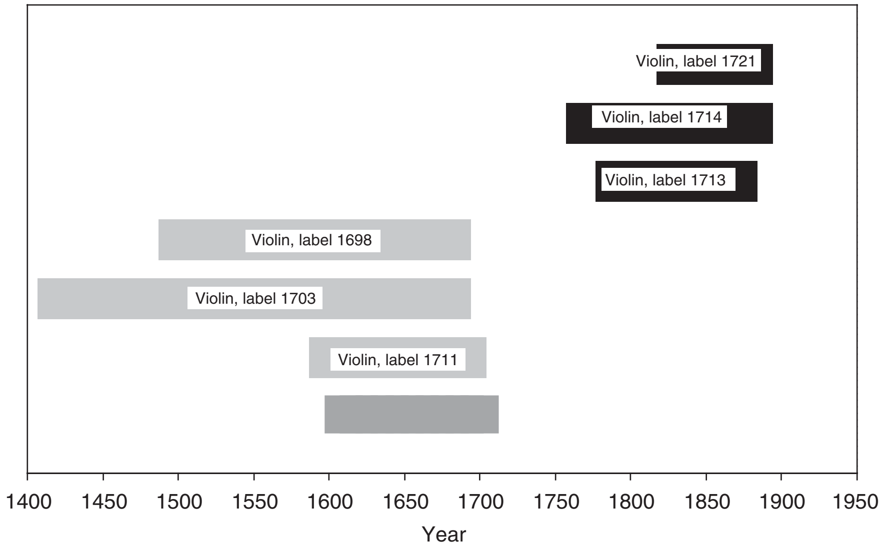

Figure 13 Tree-ring sequences of dendrochronologically dated violins which mostly were labeled as 'Stradivari.' The left-hand group probably were built by the famous master, while the wood of the right-hand group was still growing in the forest after his death.

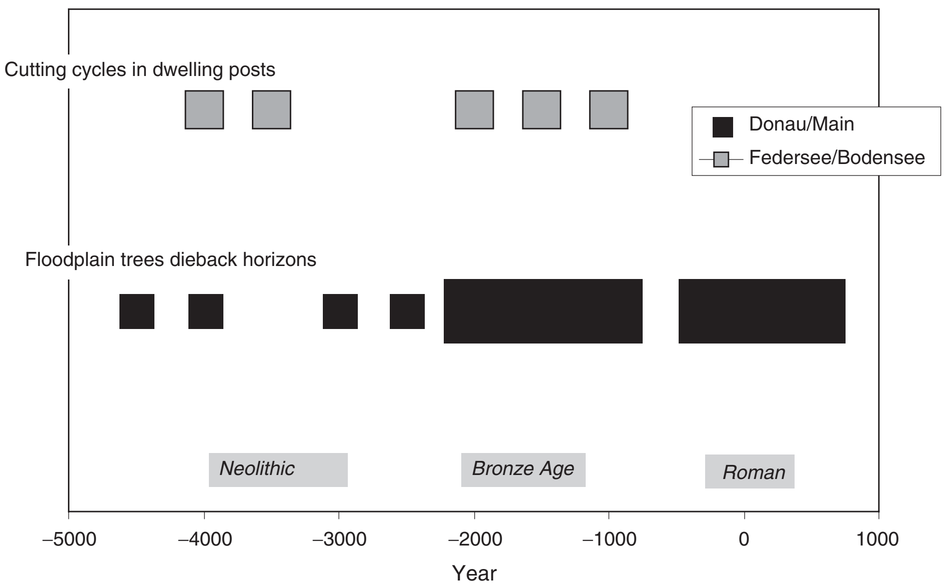

Figure 14 Dieback horizons of oak in southern German floodplain sediments and felling intensity around Bronze Age and Early Iron Age villages. Increasing clearing of the landscape and agricultural use led to an increase in erosion followed by sedimentation in river valleys. The intense dynamic probably led to the dieback of oaks in the floodplain forest.

Dendrochronology also contributed extensively to the knowledge of prehistory of human settlements. In southern Germany, the British Islands, and Switzerland, detailed information on prehistory since the Neolithic and the Bronze Age is known from excavation of dendrochronologically datable wood. During the building phases the surrounding areas of the villages were deforested for agricultural purposes, construction, and fuelwood. Since the early farmers settled on the best and deepest soils, erosion started and rivers changed their courses due to increasing sedimentation. This is visible in the ages at death of oaks excavated from alluvial soils in the floodplains. Several 'dieback horizons' are visible. The last and most distinct appeared during the Roman empire in southern Germany (**Figure 14**).

Climate Reconstruction

One of the most important applications of tree-ring analysis is the reconstruction of past climate. Most reliable climate records start in the second half of the nineteenth century. This is not long enough to judge whether the present global warming has natural correspondences in previous centuries.

As a first step it is necessary to understand the relation between climate and growth in different species. The main problem is that the two variables, temperature and precipitation, act in a complicated and often contradictory way: in the temperate zone high precipitation is related to a relatively cold summer and high temperature to a dry summer. One attempt at solving this problem is the use of samples from sites where one of the two factors is limiting such as temperature in high altitudes. In the tropics, however, the temperature is constant and only rainfall varies.

Analysis of pointer years or discontinuous time series Strong stress-related events like abnormal frosts in spring, exceptionally dry summers, prolonged flooding, insect attacks, and others are usually visible in tree-ring patterns as a 'pointer year.' One example can be traced back to the eruption of the volcano Katmai in Alaska, which occurred on 6 June 1912. The dust particles in the stratosphere then reduced solar radiation. The following August and September in some regions of the northern hemisphere were the coldest in 120 years of temperature records. Coniferous trees at higher altitudes stopped growth abruptly and could not develop typical latewood. In consequence the latewood density in 1912 is much lower than in the neighboring rings.

Analysis of tree-ring sequences or continuous time series The existence of at least two climate variables influencing tree growth requires multiple correlation analyses; the most common is the response function. **Figure 15** gives an example of the regression between ring width and climate at higher elevations. Precipitation and temperature are differentiated monthly back to June of the previous year. This is based on the assumption that climate conditions of the preceding year influence storage of carbohydrates and thereby affect the increment of the current year. Values of the previous year shift between positive and negative influence from one month to another. The results for temperature of the current year follow a clear and interpretable trend with strong positive correlation in June and July.

Reconstruction of climate The relation between late summer temperature and density of latewood allows the reconstruction of pre-instrumental climate history. Time series of density and/or ring width can be used as climate 'proxies' and show events such as the 'Little Ice Age' at the beginning of the seventeenth century and the 'Medieval Warm Period' in the northern hemisphere. One of the longest and probably most reliable climate-sensitive chronologies gives hints of an unusually cool period in the ninth century. This may be one cause of climatic catastrophes in that period and the stepwise extinction of the Maya culture in Central America (**Figure 16**).

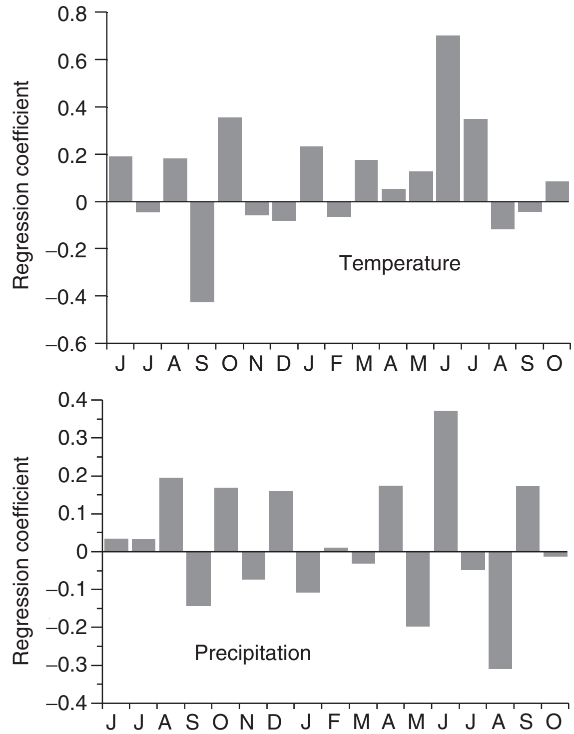

Figure 15 Multivariate analysis of the relation between tree-ring width of high-altitude (about 700 m) spruce trees (*Picea* spp.) and the climate variables precipitation and temperature. Each variable is split into monthly subvariables from June of the previous year (before formation of the tree ring) to October of the current year.

Tree-ring series in the tropics reflect variation in precipitation. One important periodical climate event in the tropical Pacific region is the Southern Oscillation-El Niño Effect. The occurrence of this weather effect was described in 1931 by analyzing a teak tree-ring chronology from Java (**Figure 17**). A recent investigation of tree rings from a floodplain tree species shows the influence of El Niño on precipitation anomalies in the Amazon basin. It seems that its strength increased and its period decreased slightly from the nineteenth to the twentieth century.

Landscape Ecology and Geomorphology

One of the simplest features of a tree-ring sequence, the age of the tree, is most valuable for the detection and interpretation of the movement of glaciers and

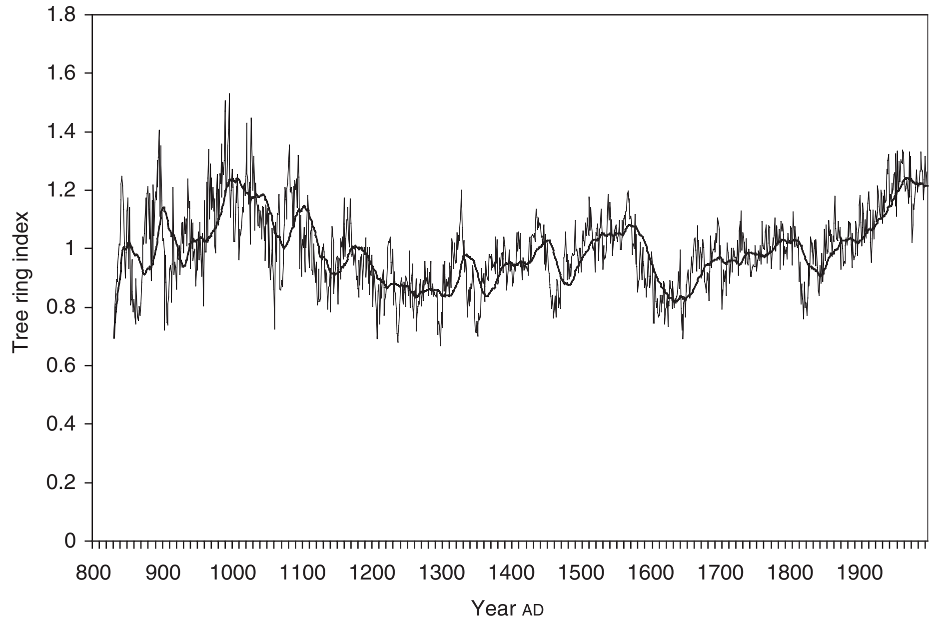

Figure 16 Temperature-sensitive chronology from the northern hemisphere. The chronology is constructed of 1205 individual tree ring series from different species (genera *Picea*, *Pinus*, *Larix*, and *Abies*). Trees origin from 14 high-elevation or high-latitude sites and from the entire Northern hemisphere. The 'Medieval Warm Period' and the 'Little Ice Age' as well as recent global warming are clearly shown.

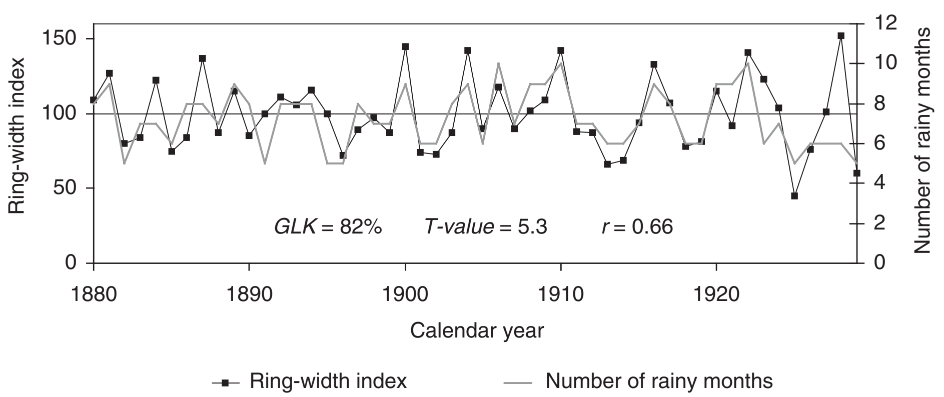

Figure 17 The Java teak (*Tectona grandis*) chronology of Berlage from 1931 shows the concurrence between tree-ring width and precipitation, which is expressed as duration of the monsoon. The tree-ring curve is detrended. The periodical pattern of recurring minima and maxima reflects the influence of the El Niño-Southern Oscillation effect. Berlage was the first to detect the influence of El Niño in tree rings. The graph only shows the latest period of the chronology, which goes back to 1514. GLK, Gleichläufigkeit.

the dynamics of rivers. In the case of glacier dynamics the age of the pioneer trees that follow its retreat can be estimated easily. Information on the course and frequency of avalanches, landslides, mudflows, and stonefalls can also be gained from trees surviving with datable damage to crowns or stems. This information provides estimates of the degree of danger for newly constructed roads and buildings in mountain areas.

Forest Dynamics, Ecology, and Management

Information on forest growth is important for sustainable forest management. Changing environmental influences such as the increasing acid emissions in the twentieth century, fertilization through increasing N deposition, temperature, and damage due to pests and storms require a tool for fast measurement of growth reactions to these factors. In the tropics the current state of knowledge on growth rates and forest dynamics is extremely poor due to the lack of reliable yield tables and the assumed absence of tree rings.

Forest dynamics European forests have been managed intensively for centuries. The network of monitoring and documentation often is dense. However yield tables are based on means and undisturbed situations. Changes of site and environmental conditions are usually not considered. Thinning and

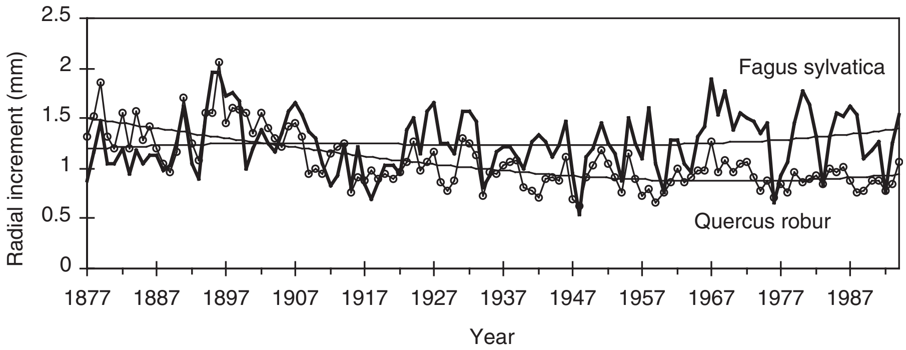

Figure 18 Ring-width curves: raw data and long-term trends of oak (*Quercus robur*) and beech (*Fagus sylvatica*) trees growing at dry sites on steep slopes and shallow soils. Beech outcompetes oak from the beginning of the 1930s. Presently their crowns are at least 3–5 m higher than oak.

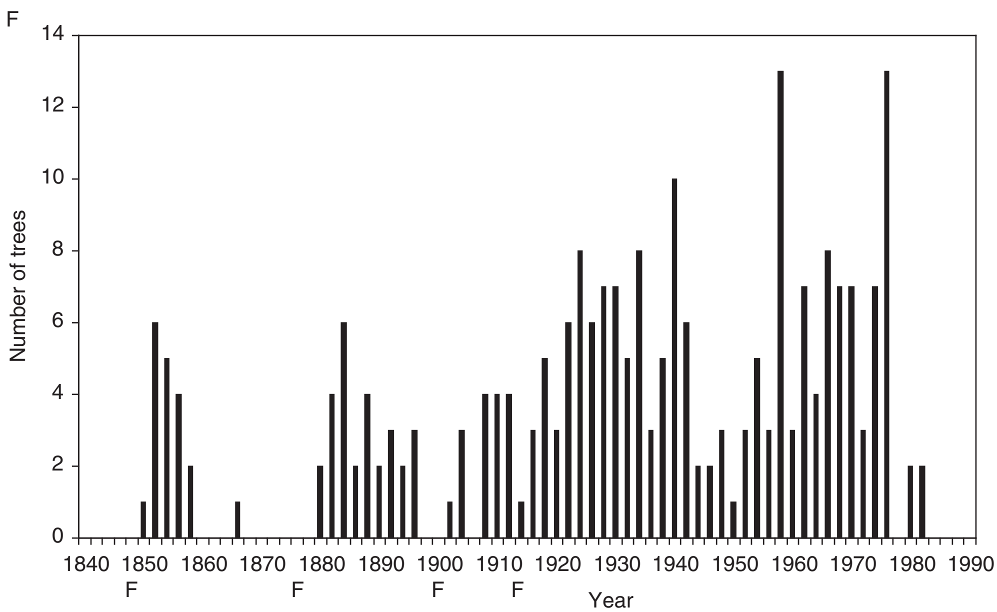

Figure 19 Age structure for *Pinus banksiana* from a boreal site in Canada affected by forest fires. The fire years are identified by age dating of fire scars and abrupt changes in radial increment.

spacing have the effect of increasing the growth of the remaining individuals, whereas growth reductions take place after storms, when trees are partially damaged but survive, and when pests like budworms effect a recurring pattern of pointer years. Competition between species can be described by interpreting long-term trend curves. The example in **Figure 18** explains the predominant growth of beech (*Fagus sylvatica*) in comparison with neighboring oaks, even on the driest sites, where recent ecological knowledge had postulated the opposite.

In certain ecosystems frequent catastrophic events trigger the regeneration of the forest. This is the case after hurricanes, after erosion and sedimentation in floodplains, and after intensive forest fires. These are necessary for regeneration in some temperate and boreal coniferous forest ecosystems. Fire scars in the wood help to identify the fire frequency (**Figure 19**).

Tree decline In the late 1970s in Europe and North America the sudden devastation of entire forest stands, mainly of coniferous tree species, forced an intensive search for its causes and for the basis of prediction of future development. It soon became clear that the deposition of acid rain on unbuffered soils was one of the major causes. In this context tree-ring analysis was the best tool for the comparison of growth trends before and after the intense influence of acid rain. Tree rings show clearly the decrease of increments in heavily polluted areas.

The percentage of trees with increment losses declined with decreasing altitude, and on calcareous

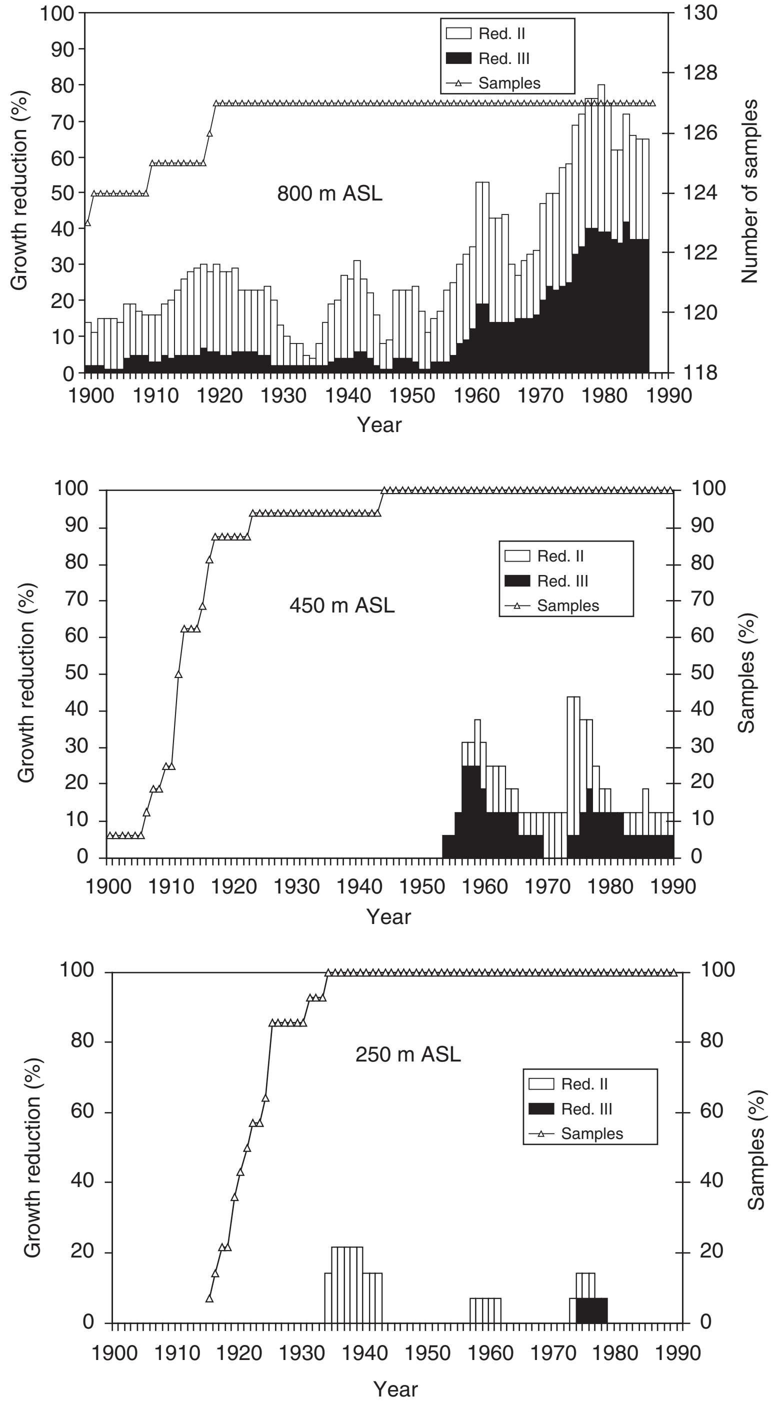

Figure 20 Number of spruce trees (*Picea* spp.) with growth reduction in relation to total sample from different elevations in Northern Germany. Trees from high elevations (ASL, above sea level) show partially letal growth decline since the beginning of the 1960s. Sites were mainly orientated on western slopes of the mountains, where emissions from the Rhine/Ruhr industries are transported on the prevailing wind.

soils in the lowlands the problem was clearly not existent (**Figure 20**). The main agent of damage was sulfur dioxide. Based on tree-ring studies Switzerland enacted new laws aimed at reducing emissions of sulfur dioxide. The reduction was followed by a slight increase of tree growth.

Sustainable forest management in the tropics Many tropical forests are managed intensively, but one way to avoid overexploitation is to support sustainable management systems. Many key factors for timber certification have been developed, but it is still unclear how fast trees grow. However, the existence

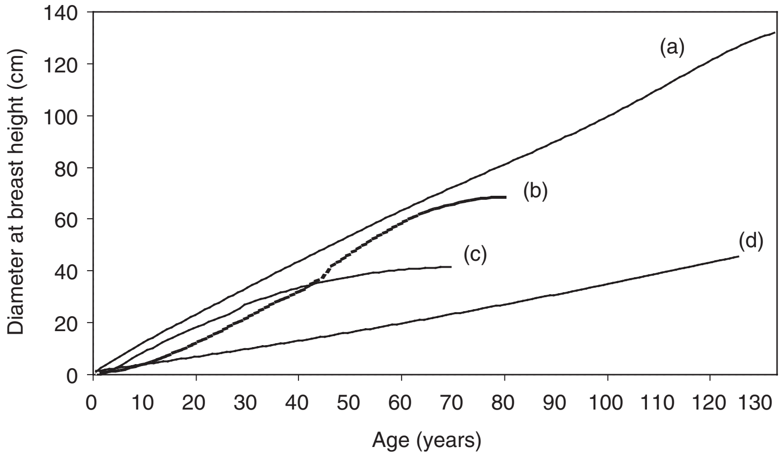

Figure 21 Mean cumulative diameter increments of the softwood species (a) *Triplochiton scleroxylon* from Cameroon and (b) *Macolobium acaciifolium* from the Amazonian floodplains. The growth of the hardwood species *Tabebuia barbata* varies according to origin: (c) from a natural secondary forest and (d) a mature forest, indicated by distinct differences in the shape of the long-term trends. Each curve is a mean curve of 5–20 individuals.

of distinctive annual rings, e.g., in the main West African timber species, has been known for more than 30 years. One of the faster-growing species there is *Triplochiton scleroxylon*, which needs 70 years to reach the minimum logging diameter. In Amazonian floodplain forests, trees of different wood densities and growing environment need different time to reach the cutting diameter (**Figure 21**). A species-specific management system would help to establish more economical use than the recent system with identical measures for all species.

Conclusions and Outlook

'For 70 years dendrochronology was a purely academic science; today certain aspects have become accepted in the sphere of applied sciences.' This statement of Fritz Schweingruber from 1986 is even truer today. Progress can be traced back to the personal dedication of some promoters of tree-ring science, writing textbooks, organizing conferences, teaching students, and running internet sites. However, the main cause of dendrochronological success is the scientific work on modern themes leading to accepted studies in most of the abovementioned fields of research.

Acknowledgment

We are indebted to Margaret Devall, Stoneville, MS, for her careful review, useful suggestions, and substantial linguistic improvement of the manuscript.

See also: **Ecology**: Natural Disturbance in Forest Environments. **Environment**: Impacts of Elevated CO_2 and Climate Change. **Tree Physiology**: Physiology and Silviculture. **Wood Formation and Properties**: Formation and Structure of Wood.

Further Reading

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