POLSKA AKADEMIA UMIEJĘTNOŚCI
KOMISJA PALEOGEOGRAFII CZWARTORZĘDU

# FOLIA QUATERNARIA 79

ELŻBIETA SZYCHOWSKA-KRĄPIEC

# LONG-TERM CHRONOLOGIES OF PINE (*PINUS SYLVESTRIS L.*) AND FIR (*ABIES ALBA MILL.*) FROM THE MAŁOPOLSKA REGION AND THEIR PALAEOCLIMATIC INTERPRETATION

KRAKÓW 2010

Redaktor tomu:
Witold Zuchiewicz

Redaktor techniczny:
Jarosław Brzoskowski



ISSN 0015-573X

POLSKA AKADEMIA UMIEJĘTNOŚCI
KRAKÓW 2010
Obj.: ark. wyd. 7; ark. druk. 7,75; nakład 500 egz.
Druk i oprawa: Poligrafia Inspektoratu Towarzystwa Salezjańskiego

CONTENTS

FOLIA QUATERNARIA 79, KRAKÓW 2010, 5–124
PL ISSN 0015-573X

# LONG-TERM CHRONOLOGIES OF PINE (*PINUS SYLVESTRIS L.*) AND FIR (*ABIES ALBA MILL.*) FROM THE MAŁOPOLSKA REGION AND THEIR PALAEOCLIMATIC INTERPRETATION

Elżbieta Szychowska-Krąpiec

Abstract. The studies aiming at construction of long incremental patterns for two coniferous tree species, *Pinus sylvestris* and *Abies alba*, from the Małopolska region were initiated at the Dendrochronological Laboratory of the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Kraków in the mid-1990s. These studies, successfully finished, resulted in two regional chronologies: 916-year pattern for the pine (1091–2006 AD), and 896-year fir chronology, covering the period 1109–2004 AD. Both these chronologies, exhibiting high similarity to the regional chronologies from the adjacent areas, are being used for dating wood from archaeological sites, architectural objects or mining excavations. Except for the primary goal, i.e. absolute dating of wood samples, they were also used as the proxy data in the prediction of the temperatures December-March (fir) and February–March (pine) for the last 900 years. In this way, the distinguished periods of cooling and warming fit in the general pattern of the long-term climate changes: the Mediaeval Warm Period, the Little Ice Age, and the Recent Global Warming. Some of the cool phases are convergent with the Wolf, Spörer, and Maunder Minima of the solar activity (sunspot populations). Short-term, but drastic changes of the climatic factors are marked in the chronologies newly constructed as the positive or negative signature years. The response function analysis demonstrated the positive dependence of the annual increments of the pine on the temperatures of two winter months (February–March) and the fir on the temperatures of the entire winter period, from December till March.

Key words: dendrochronology, dendroclimatology, reconstruction, pine, fir, Małopolska region, south Poland

Author's address: Elżbieta Szychowska-Krąpiec, Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland; E-mail: szycha@geol.agh.edu.pl

# INTRODUCTION

The studies aiming at construction of several-hundred-year long chronologies for wood of the pine and fir from the Małopolska region have been conducted by the author at the Dendrochronological Laboratory of the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Kraków, for many years. Gathering wood representing various time intervals, which would enable to create such standards, started in the middle of the 1990s. The material for the analyses was collected, among others, from wooden structures of ceilings and roofs of numerous churches and secular objects. It also came from archaeological excavations led in Kraków as well as in its close and more distant surroundings. Historic salt mines in Bochnia and Wieliczka proved to be an invaluable store of wood; they provided a row of wood samples of various ages, coming from casings of the mining excavations. Thanks to rather common presence of the fir wood in architectural objects, archaeological excavations, as well as mining casings, the studies on the fir standard could advance without serious obstacles. In the case of the pine wood, however, some problems appeared, especially with wood representing the older periods of time; the seventeenth century and further backwards. The pine chronology, constructed by the author in 1997, served as a standard for dating the pine wood from the Małopolska region, but its main handicap consisted in its relatively short (375 years) temporal extent. Therefore, all the time the pine wood representing older periods has been searched in the whole Małopolska region. Nevertheless, neither in archaeological excavations, nor in wooden structures of various objects in Kraków or south of Kraków such old pine wood was come across. This was probably connected with the fact that in former centuries the pine only occasionally appeared in the natural tree stands in the region. The participation of this tree species started to grow only in the times of the Austrian administration, when it was gradually introduced into the Małopolska forests, especially in the vicinity of Kraków. This situation is very well reflected in the Wieliczka Salt Mine, which contains huge amounts of wood from different periods of time, but it is hard to encounter any pine wood among the oldest timbers from the fourteenth to sixteenth centuries. Only at the beginning of 2000, when broadly conceived excavation works were undertaken in the Central Market Square in Kraków and in Zakrzów near Niepołomice, some timber structures, in part made of pine wood, were found. Thanks to these two sites it was possible to compile the oldest 300 years in the 900-year pine chronology. The situation with the pine wood looks a little bit different to the north and north-east of Kraków. In these areas, the pine wood appears in the structures of wooden objects dating back even to the distant times (the $14^{th}$, $15^{th}$ and $16^{th}$ centuries). For instance, the elements made of the pine wood occur in the roof structures of numerous churches (Chotel Czerwony, Chroberz, Krzcięcice, Zborówek). This created the perspectives for construction of the standard reaching further back in time. The research performed was aimed at establishing patterns enabling dendrochronological dating, in form of long regional standards, as well as their palaeoclimatic interpretation. These goals have been achieved. The study presents two new regional standards for wood of *Pinus sylvestris* and *Abies alba* from Małopolska, covering 900 last years. The standards were also based on some additional timbers sampled from architectural objects and archaeological sites from the Upper Silesia and Holy Cross regions, which improved their replication and sensitivity.

These standards constitute a base for dating a row of objects, such as:

– wooden casings of historic excavations in the Wieliczka and Bochnia Salt Mines,
– historic churches, at which the times of their construction, reconstruction, or repairs were determined,
– artefacts of urban mediaeval buildings, coming from archaeological excavations.

An annual tree-ring carries the record of the history of its formation. The information contained in the annual tree-rings is an excellent archive of both biotic and abiotic environmental data. They, in turn, allow for palaeoenvironmental analyses aiming at reconstruction of various extreme events, which took place in the past, e.g. volcanic eruptions, fires, floods, unusually harsh and frosty winters. The ability of appropriate reading and interpretation of such data offers a great potential of the possibilities of reconstruction of such events, which did occur in the time of growth of the trees. The chronological record of the environmental conditions, year after year, is legible in both coniferous as well as deciduous tree species, and remains unchanged all the time (Baillie 1995).

The tree-rings are also a natural climatic 'archive'. For several decades dendroclimatical studies have been undertaken, the purpose of which was the prediction of climatic conditions in the past and in the future, and the annual growth rings proved to be the perfect proxy data. In general, for mountain regions the temperatures were reconstructed, however, in lowland areas – the precipitation totals were approximated as well.

Elaboration of the new standards allowed for carrying out the studies of that type for the Małopolska region. Their palaeoclimatic interpretation enabled to distinguish the periods of cooling and warming in Małopolska in the last 900 years, as well as the periods of particularly disadvantageous temperatures ruling in the entire winter period, from December till March, and at the end of winter, in February and March. The distinguished periods of cool winters are reflected in the periods of the lower activity of the Sun, defined with the Wolf, Spörer, Maunder, and Dalton Minima. They also fit in the long-term climatic changes, registered not only in Poland or Europe, but in the entire world: the Mediaeval Warm Period, the Little Ice Age, and the Recent Global Warming. The dendroclimatic analyses also enabled to determine the influence of the temperature and rainfall on development of the annual growths at both tree species in the period of the intensified industrial activity after the Second World War, as well as before the industrial period. The compiled sequences of the annual growths permitted for determination of the signature years, resulting from the appearance of exceptionally adverse climatic conditions in winter (harsh, frosty and long winters) and in summer (abundant rainfall, floods, droughts). The results of the presented research will find application in the studies conducted both in Poland and abroad, because the Polish wood has been imported to Western Europe since the Middle Ages.

The study and its effects presented in this paper would not come off without help of many persons, very kind and helpful for me, whom I am not able to mention all here. ‘Infecting’ me with the dendrochronology, teaching me the principles, gaining the professional experience I owe to my husband, for whom I want to say THANK YOU. I would like to thank Assoc. Prof. Dr. Włodzimierz Margielewski for his help in taking samples and valuable remarks pertaining to this contribution. The advice provided by Assoc. Prof. Dr. Adam Walanus at the stage of writing is highly appreciated. I would like to thank Prof. Dr. Andrzej Zielski for his help in taking samples and the time devoted to me at work on this study. Words of appreciation are directed to the geologists from the Wieliczka and Bochnia Salt Mines for the time devoted to taking samples and for their kindness and engagement in the work. My cordial thanks also go to Dr. Krzysztof Dudek, Paweł Krąpiec, M.Sc., and Maciej Borowiec, M.Sc., whose help at work on this study was invaluable.

The research was financed in part by the Faculty of Geology, Geophysics and Environmental Protection AGH–UST in Kraków, in the framework of the statutory research no. 11.11.140.560.

## BIOLOGICAL BACKGROUND TO DENDROCHRONOLOGY AND CHARACTERISTICS OF THE INVESTIGATED TAXONS

The research material of dendrochronology is wood containing annual increments (tree rings). Presence of annual rings is characteristic for the trees growing in conditions of moderate climate, where the cambium activity is connected with the seasons, regularly following one another. In the vegetation period (spring-summer) it usually produces one annual growth, whereas in the resting period (autumn-winter) the division-cambium activity fades out. The pulp behaves differently in the tropical climate conditions, in which there is no resting phase induced by the seasonal character of the climate. Hence, in the tropics its activity is permanent, but it does not always lead to development of the annual rings. Instead, some incremental zones, connected with periodic climatic variations, may be observed. The cambium activity is an individual feature of every tree, not always corresponding to the annual cycle (Tomanek 1997, Zielski and Krąpiec 2004). In case of the trees in Poland it starts in spring, thanks to growth regulators (auxines, giberelines, vitamines, and inhibitors) (Hejnowicz 1967). Usually, the effects are firstly visible in young shoots and thin branches, and only later in lower parts of the plant, such as the trunk and roots.

At the Scots pine, the most common of the Polish trees, in the conditions of Central Poland the period of the cambium activity lasts from 75 to 150 days; it starts between the third decade of April and the third decade of May and ends between the first decade of August and the second decade of September. The terms of the beginning and the end of the cambium functioning are controlled genetically and they depend on the genotype changeability (Wodzicki and Zajączkowski 1983). At the silver fir (*Abies alba*), the cambium activity starts somewhat earlier, in the first week of April, and lasts until the end of August (Golinowski 1971).

In the period of its activity the cambium produces new cells of the bast (phloem) outwards and new cells of the wood (xylem) inwards. The time of the beginning of the cambium functioning is highly variable, not only at various tree species, but also within the same species. Formation of new cells of the phloem most often precedes ripening of wood elements about a few weeks, e.g. at the fir the early phloem forms from 7th April to 1st May, whereas the earlywood from 20th April to 1st June. After a temporary rest, the cambium starts producing the latewood, which at the fir begins to form between 15th July and 30th August (Golinowski 1971). At the pine, the latewood begins to form earlier, already at the end of May, though the beginning of this process may be shifted till the end of July (Wodzicki and Zajączkowski 1983).

Every layer of wood formed within the vegetation season constitutes an annual tree ring. At the coniferous tree species, the borders of the tree rings are well recognizable, because the earlywood zone is characterized with light colouration and the tubules exhibit large light and thin cell walls, whereas the latewood zone is dark and the tubules have thicker cell walls and narrow lights.

The number of tree rings in a trunk, branch, or root usually corresponds to the age of a given organ, but the closer the top a given cross-section is situated, the lower the tree-ring number, which is related to the top growth of a given tree organ. It may happen, however, that in a given vegetation season an annual increment is not developed. In certain conditions the tree rings could not form at all, whereas in other situation they could double. The phenomenon of the missing rings occurs when in a given vegetation period the tree produced the new growth only in a part of the trunk perimeter or did not develop it at all (Krzysik 1974). This may seriously hinder determination of the tree age on the basis of the tree-ring figures. Missing rings may be encountered quite often at the coniferous tree species, such as pine, fir, spruce, and larch. Their number is dependent on the tree species and the environment, e.g. at the larch the missing rings occur more often than at the spruce growing in the same conditions (Schweingruber 1996). Adverse environmental conditions, caused by e.g. overshadowing, may result in missing rings. The air pollutants, emitted by the industrial plants, may contribute to the phenomenon of the missing rings as well. Various tree species react differently to this factor. The most immune, deciduous trees do not exhibit any strong tendency for changes of that type, thanks to annual shedding leaves for the winter. At the coniferous taxons, however, the impact of the industrial pollutants is often reflected by the missing rings or substantial reductions in their width. It is so at the fir, pine, and spruce, contrary to the larch, of which reactions to the industrial stress are similar to the deciduous species (Krąpiec and Szychowska-Krąpiec 2003).

The phenomenon of the missing rings is quite frequent at trees growing on peat bogs, where high level of groundwater causes disturbances in the incremental sequences of trees (Schulthess 1990, Pukiene and Bitvinskas 2001, Eckstein *et al.* 2008).

It may happen that in a given vegetation season more than one increment is produced; so-called double rings are observed. They may form e.g. when in a single vegetation period the tree repeatedly produced new foliations, due to some adverse conditions (spring frost, gradation of insects, etc.).

The width of the annual growth formed depends on many factors:

– the tree species and its individual features,
– the tree age,
– sensitivity to the environmental factors,
– abiotic factors, such as: light, temperature, water, rainfall, wind, mechanical damages of the canopy, roots, or branches, pollutants (Schweingruber 1996).

The trees of one single population react similarly to the environmental changes, developing narrower or wider annual growth rings, appropriately. The annual growth width R may be expressed with the following formula (Cook 1990):

$$R_t = A_t + C_t .+ dD1_t + dD2_t + E_t$$

where:

*A* – the age trend reflected in the tree-ring width and connected with the growth of the trunk in thickness,
*C* – the climatic component,
*D*1 – the element impeding growth of individual trees of the population (e.g. mechanical damages of the trunk),
*D*2 – the element impeding growth of trees of the entire forest population (e.g. insect attack, changes of the groundwater level),
*E* – the invisible element,
*t* – time,
*d* – binary indicator of the presence ($d = 1$) or lack ($d = 0$) of a given element.

Some trees have a natural tendency to formation of wide or narrow annual growth rings, e.g. fast growing poplars are characterized with wide annual growths, unlike the narrow-ringed, long-living pine trees (*Pinus longaeva*) (Vaganov *et al.* 2006), growing slowly and reaching the age of over 4000 years. Narrow annual growths are also characteristic for the trees growing on the border of the vertical or horizontal extent of their appearance. On the other hand, wide rings often occur at young trees, so-called juvenile growth rings; such rings are also common at the trees growing in the zones of their optimal growth (Tomanek 1997). At all trees, however, narrowing of the growth rings may be observed, which is connected with exceeding a certain age and beginning of so-called senile trend, brought about by decreasing of the metabolism parameters (Schweingruber 1996).

Heartwood formation is also connected with the age of the trees. After achieving a certain age, the heartwood forms at various tree species, e.g. at the pine it starts between the 20th and 70th year, and at the fir – at about 60-70-year-old trees (Schweingruber 1996). The heartwood usually differs from the living part of the trunk, the sapwood, with the colouration (as a rule it is darker, e.g. at pine, larch, yew, oak, nut – so-called heartwood trees), as well as with lower contents of water, higher weight and hardness. As a result, this part of the trunk is more resistant to mechanical and biological damages (Tomanek 1997). Apart from the trees with coloured heartwood, there are such species, at which both the sapwood and heartwood exhibit similar colouration (fir, spruce, lime tree), or such ones, which are totally devoid of the heartwood (hornbeam, beech, birch, alder). The sapwood is the outer, living part of the trunk, consisting of the increments formed in the last vegetation periods and responsible for storing spare substances and conducting water (Tomanek 1997). The number of the tree rings in the sapwood depends on the tree species as well as on the environment in which the tree grew. At the oak, the sapwood encompasses from a dozen or so to over twenty growth rings, depending on the region of Poland, whereas at the pine that number can reach even a hundred, and even at a single tree it is not constant on various cross-sections (Zielski and Krąpiec 2004).

One of the most important tree species in the dendrochronology is the Scots pine. It is characterized with large territorial extent, the largest of all the species of the genus *Pinus*. Its extent from the east to the west reaches 14,000 km, from Spain till the Far East of Russia, and in the north-south direction as much as 2,700 km, from Northern Norway till the Sierra Nevada Mountains in Spain. In Poland, this species is predominating in the entire lowland regions, and of a lesser forest-forming importance – in the Sudetes and Carpathian forelands. In the mountains, beyond the borders of its natural occurrence, the Scots pine is not very common (Boratyński 1993).

Scots pine is the tree species characterized not only with large territorial extent, but also broad adaption abilities. Being one of the boreal-mountain tree species, connected with the continental climate, the Scots pine occurs in the areas with the temperatures ranging from minus 60°C to plus 40°C and the annual rainfall between 200 mm in Yakutia and 1000 mm in the mountains of Spain. It is also tolerant to the height amplitude; from coastal sites until over 2000 m a.s.l. in the Alps or the Pyrenees (Przybylski 1972). On the account of these features, the Scots pine was chosen as the subject of the pan-European research project ISONET focused on the climate changes in the last 400 years. They were reconstructed on the basis of C, H and O stable isotopes in the cellulose of the wood separated from individual annual growth rings. Such studies could be done thanks to large longitudinal extent of the Scots pine, from the eastern to the western borders of Europe, and also latitudinal one – from the north to the south of the continent.

In several last centuries the pine has been omnipresent in various habitats and in many different regions of Poland. Hence, it is a taxon, the wood of which was readily used as the building material in almost entire Poland. The pine wood is often encountered in timber structures of numerous mediaeval objects and relics found at the archaeological excavations in the Polish Lowland regions. It is, however, substantially less common in Southern Poland, in the regions of Małopolska and Podkarpacie. Because of its high changeability, connected with the diversity of the environments in which it occurs, the pine exhibits highly diversified incremental patterns, sometimes considerably divergent ones. The dendroclimatical analyses, carried out on 136 tree stands of the pine from various geographical and climatic regions of Poland, resulted in distinguishing nine dendroclimatic regions of Poland, on the basis of the resemblance of the pine incremental patterns (Wilczyński *et al.* 2001). Various rhythms of the annual growths of the pine in various regions cause considerable problems with the absolute dating of pine timbers, especially from Central and South-Western Poland. For instance, dating of historical pine wood from the surroundings of Wrocław proved to be particularly difficult, because the samples analysed exhibited different incremental trends and numerous disturbances of the growth structure. Moreover, such a material is characterized by a relatively low number of tree rings; quite often historical wood contained from 30–40 to about 100 growth rings. On the other hand, in the regions of the continental climate (e.g. Suwałki region), the incremental patterns of pines are quite similar, so the dating could be done without any substantial problems. In the case of the pine the presence of the last, youngest growth ring is essential in dendrochronological dating, because the highly variable number of the sapwood rings on a cross-section does not permit for dating with a several-year accuracy, which could be possible, for instance, in the case of oak.

On the other hand, silver fir is a tree species, which presents relatively least problems in the dendrochronology. The fir is often described as a tree of low mountains; it occurs in the mountains of Central and Southern Europe; the northern border of its European extent runs through Poland. As the forest-forming tree species it appears in the uplands of Central and Southern Poland, in the Roztocze region, the Holy Cross (Świętokrzyskie) Mountains, and in lower parts of the Carpathians. It is a tree of moderate cool and humid climate, and its presence is dependent on the average annual temperature, which cannot drop down below 5°C, whereas the average temperature of the vegetation period should not be lower than 13–14°C (Jaworski and Zarzycki 1983). The fir is the species, which has higher thermal requirements than the pine, the maximal summer temperatures should not exceed 39°C, and the winter minimum – minus 27°C. The optimal conditions for its growth are in the temperature range from minus 4.5°C (average temperature of January) to 15°C (average temperature of July) (Jaworski and Zarzycki 1983). In terms of the rainfall, the fir is also the more sensitive taxon than the pine. In the case of the fir the minimal annual rainfall should not be lower than 600 mm.

The fir is characterized with clear and distinct tree rings, the phenomenon of missing rings appears only rarely. The fir wood is frequently encountered as relics in archaeological excavations (from the western border of Poland – Żary, Świdnica, through Southern Poland – Upper Silesia, Małopolska, all the way to the eastern parts of the country – Krosno, Sanok) (Szychowska-Krąpiec 2000). It appears equally often in timber structures of various sacral objects; e.g. church in Haczów, Orthodox church in Ulucz, Orthodox church in Ropki, collegiate church in Wiślica. Incremental patterns of the fir are characterized with high mutual similarity, which considerably facilitates absolute dating, even of samples coming from distant areas. Therefore, in the case of this taxon numerous samples could be successfully dated. An essential feature is also the fact that even relatively short sequences, containing about 30 tree rings, are suitable for the dendrochronological analysis, which does not practically happen at other tree species At dating the fir wood, like at the pine, the presence of the youngest annual growth is important for precise dating with the one-year accuracy.

## METHODOLOGY OF DENDROCHRONOLOGICAL RESEARCH

At every tree species annual growth rings display a record of growth conditions of a given tree and of everything which happened to it in the past. The tree rings form an individual pattern, characteristic for every tree, in which, like in the calendar, year after year all essential factors affecting its formation are written. Depending on the age of the tree and its longevity, such patterns may contain various numbers of growth rings (increments); from a dozen or so to several tens or even hundreds. From a point of view of the dendrochronology, only the trees which contain at least fifty annual rings are useful for analyses, though in the case of the silver fir this number may be lowered, as mentioned above, to about thirty. Generally, the higher the number of the tree rings forming the individual sequence in the examined sample, the easier the dendrochronological dating should be.

No matter the tree species, samples for the dendrochronological studies are being taken in the form of circular slices, wedge-shaped fragments, or cores. The samples most desirable by the dendrochronologist are in the form of slices, cut perpendicularly to the trunk at the height of about 1.3 m from the root zone, containing the whole incremental sequence of tree-rings, from the oldest to the youngest ones, and including the total sapwood layer with the last, youngest growth ring. Such samples are most often taken from relic timbers in archaeological excavations, dismantled structural elements, e.g. roof structures, casings of mining excavations, as well as in other cases, if only taking a sample be safe for both; the sampled wooden structure and the sampling dendrochronologist. Circular slices are preferred, because they offer the opportunity of measuring an individual sequence in several different places. It is essential at growth rings locally disturbed, snags, damages caused by wood-eaters, or other deformations. Most often several radii are being prepared for the measurements of the annual growth widths, and the individual sequence (pattern) is elaborated through averaging the incremental sequences measured.

Taking samples in such a form, however, is not always possible. Wherever it is impossible, the sampling is carried out with coring borers for the dry wood, driven with an electric drill of high power. The cores collected this way are 15 mm in diameter. Such a sampling requires certain precision and experience, because gathering a core containing the incremental sequence with the total sapwood layer is neither straight nor easy.

Wood samples may be collected relatively easily with the Pressler increment borer. It is most often used for taking cores from living trees; depending on their thickness the borers of 40 or 60 cm are applied, occasionally even longer ones (100 cm). Such borers may also be successfully used for taking wood samples from casings of mining excavations or various wooden devices in the mines. This way of taking samples proved to be highly effective in salt mines, at sampling wood of coniferous tree species. In slightly humid wood, saturated with brine, the borer is advancing in relatively easily, the only inconvenience being the fact that in the salty milieu it quickly becomes dull, which requires repeated sharpening. Most often the borers of 5 mm in diameter are used.

During the studies performed by the author, the samples were taken in both forms – slices and cores. The samples for dendrochronological analyses should contain a complete incremental sequence, from the oldest to the youngest growth, and also should have legible borders between the growth rings. All disorders which occurred in wood during its growth (double or missing rings), mechanical or biological damages render such places not suitable for measurements. The measurements were made twice or three times on radial surfaces, earlier appropriately prepared. The preparation consisted in cutting out 2–3 millimetre topcoat of wood with special preparation knives, in order to unveil its anatomical structure. The measurements, with the 0.01 mm accuracy, were made on a measurment device, composed of a moving stage, an opti-electronic set, a computer, and a stereoscopic microscope with a cross in the eyepiece and the fluid tuning of the magnification up to 100×. The averaging of the tree-ring widths measured along the selected radii results in an individual sequence, earlier presented, and a dendrogram, a graph illustrating the tree-ring widths in the examined sample.

Correlation of the individual sequences measured was carried out on the basis of comparison of dendrograms in order to get synchronous positions, i.e. such in which the compared curves are matching. This process could be considerably facilitated by using appropriate computer programs. In most of these programs two statistical parameters are being used: the value *t* and the Pearson's coefficient of the linear correlation (*r*). The value *t* was applied in the dendrochronology by Baillie and Pilcher (1973). It is calculated as in the Student's test, in the formula:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}}$$

where:

$N$ – the number of shared tree rings in the sequences compared,

$r$ – the Pearson's coefficient of the linear correlation calculated for the position analysed.

The Student's test is a continuous distribution of the probability, often used in the statistics in the procedures of testing statistical hypotheses, as well as at the assessment of the measurement errors. It assumes that the sequences compared have a normal distribution. Annual growths of trees, however, display various disturbances and diverge from such a distribution. Therefore, the tree-ring widths ($x_i$) are transformed according to the formula below, so as to eliminate the disorders and to obtain the distribution close to the normal one (Baillie and Pilcher 1973):

$$a_i = \ln \frac{5x_i}{x_{i-2} + x_{i-1} + x_i + x_{i+1} + x_{i+2}}$$

where:
$x$ – the tree-ring width before the transformation,
$a$ – the tree-ring width after the transformation,
$i$ – year.

The value $t$ is the statistical value most readily used to the assessment of resemblance of the dendrograms. It is assumed, that $t = 3.5–4.0$ is a threshold value enabling dating the individual sequences examined. In practice, the higher the $t$ value, the certain the correlation of the sequences, although it happens sometimes that $t < 3.5$ would be a value dating a given sample successfully, whereas $t = 4.0–6.0$ not always corresponds to the correct correlation of the sequences examined. The value t is the highest at correlating cored radii derived from the same tree (e.g. $t = 12$, $t = 35$).

The second statistical parameter, Pearson's coefficient of the linear correlation $r$, determines the level of the linear relation between random variables. In dendrochronology, at correlation of the individual sequences, generally the higher the value $r$, the more certain the synchronization, although, as in the case of the first parameter, exceptions are possible and sometimes a lower value of the coefficient $r$ is the appropriate value. At dendrochronological dating one should remember that not always the highest statistical values point out the appropriate correlation positions of the examined sequences; they are of help, but they should not have a decisive meaning. In every case the visual assessment of the dendrograms by the researcher is essential. Subsequent stages of the standard chronology construction are much the same; the work always starts with collecting samples of wood representing all centuries. This may encounter numerous problems and difficulties at every tree species; in some centuries the research material is ubiquitous, whereas in others it is missing. The initial stage of the chronology construction consists in establishing an object chronology. It is made on the basis of sequences of individual trees growing in a given site or wood appearing in an architectural object or an archaeological excavation. Then, the procedure of averaging the object chronologies overlapping results in a local chronology, representing incremental trends of trees growing in various ecological conditions. The next stage is a regional chronology, embracing incremental sequences of a given species from a larger area, dendrochronologically homogeneous. At its construction a method of bridge dating is used, consisting in putting older and older local patterns together and extending the chronology back till historic times. Regional chronologies are usually absolute standards, i.e. such ones which continue till the present or have been dated against other chronologies of the known age (Zielski and Krąpiec 2004). For this type of standards the replication is essential, i.e. covering of every calendar year by individual sequences. For a given year, the replication equal to ten is considered to be sufficient, because it is levelling individual variability and accentuating the climatic signal. Apart from real chronologies, standardized, residual, and Arstan-type chronologies are used in dendroclimatical studies as well. These patterns eliminate long-term tendencies and fluctuations, and exhibit short-term variability related to the climate conditions (Zielski and Krąpiec 2004).

The computer programs used in the dendrochronological analysis are the programs for the measurements of the tree-ring widths, the correlation of the growth sequences obtained, averaging them, plotting the dendrograms, constructing the chronologies and examining correctness of their construction, as well as the programs examining the relations between the annual growths and the climate.

In the research carried out, the following procedures were applied:

The TREE-RING package of programs consisting of two programs: TRMEAS and TRRAD (Krawczyk and Krąpiec 1995). The first one enabled the measurements of the annual ring widths and the computer record of the results, whereas the second program allowed for correlating and averaging the sequences measured, and, in turn, producing the average sequence depicting the tree-rings in the examined sample.

The PDRAW is a program allowing for plotting dendrograms, graphical presentation of the sequences previously measured (Krawczyk and Krąpiec 1995).

For processing the sequences obtained the programs PROT_1x and TRIAVER, worked out by A. Krawczyk, were used. Based on the value of the coefficient of the linear correlation *r* and the value *t*, PROT_1x indicated the optimal positions of synchronizing the population of the sequences examined, whereas TRIAVER allowed for averaging them, as well as for visual checking of the dendrograms for every individual sequence on the monitor. Another great merit of this program consists in the possibility of conversion of the measurement data written in different formats (e.g. Tucson, catras, avs) to the one interesting in a given situation. TRIAVER has also additional functions: calculation of the signature years at the thresholds of 80% and 90%, and counting the replication, i.e. the numbers of individual sequences occurring in a given calendar year.

The COFECHA, a freeware available on the internet, is an element of the package of the DPL programs – Dendrochronology Program Library. It was used for calculating the correlation between the sequences analysed, as well as the correlation between the chronology and its components. It also allows for detecting errors in the sequence measurements and pointing out the sequences measured and improperly correlated. The program provides the following data:

– the total number of the growth rings included in the chronology,

– the number of the correlated sequences,

– the number of the non-correlated sequences,
– the average tree-ring width in a given sequence,
– the similarity of the individual sequence to the chronology (the coefficient *r*),
– the standard deviation,
– the auto-correlation – it describes to which degree a given element of the sequence depends on the previous elements in the time series. The auto-correlation is a function which assigns to the natural argument *k* the value of Pearson's coefficient of the linear correlation between a given time series and the same time series shifted back about *k* units of time,
– the mean sensitivity – it depicts the degree of levelling the incremental curve and enables to assess the value of the reaction of the trees to the environmental stress (Holmes 1994).

The ARSTAN is a program, which was applied for converting the real values of the individual sequences measured into the sequences standardized by fitting the appropriate function with the least square method (Cook and Holmes 1986). The value of the annual growth width ($x_i$) was divided by the value of the fitted curve ($x_i^0$) corresponding to it in a given year. In the second stage, the spline function (Cook and Peters 1981) was fitted to the sequence of the indices and the indexation was repeated. The indexation of the individual sequences was carried out in order to accentuate the short- or long-term variability characteristic for all the sequences analysed and to eliminate the individual or incidental features of individual trees. In the sequences indexed the short-term variability, mainly caused by the climate, is well noticeable (Zielski and Krąpiec 2004). On the basis of the individual sequences standardized, for both tree species the standardized chronologies were established, which underlined unequivocal reactions of the trees to the external factors, exhibited by formation of either narrow or wide annual increments.

For examining the relation annual growth – climate, the RESPO program (response function) from the package of the DPL programs was used. It is based on the method of the multiple regression, in which the regression coefficients are being used for depicting the relations between the widths of the annual tree rings and the climate parameters (most often the average monthly rainfall and the temperature). The RESPO program analyses the relations climate/growth for rather long periods (most often monthly), but it is failing at short-term relations (daily or decade), because the regression method becomes too difficult to carry out (Birrong 1988). The average monthly air temperatures and the total monthly precipitation are the independent variables. The climatic data came from two meteorological stations Kraków-Balice and Kraków. They were tested with the MET program, from the package of the DPL programs (Holmes 1994), in order to define their homogeneity. The dependent variables are the values of the indices of the indexed chronologies. The analysis was carried out for the 16 last months: the months of the end of the vegetation season in the year preceding the growth, the winter months, and the months of the current vegetation season (Cropper 1982). According to Fritts (1976), these are the climatic conditions of the end of the vegetation season in the previous year, the winter months, and the vegetation period of the year analysed, which are responsible for the cambium activity and the tree-ring formation. It is assumed that the essential impact on the formation of the annual growth is exerted by the climate not only in the period of the cambium activity, but also in the former season.

The RESPO program calculates individual values of the multiple regression coefficients (*r*) for the variables: annual growth – rainfall and temperature, and selects the values significant at the level $\alpha = 0.05$. In this way, the relations between the size of growth and the climatic variables are determined statistically. Apart from the multiple regression coefficients, the program calculates the coefficients of the linear correlation (*k*) between the values of the average monthly temperature and the total monthly precipitation and the values of the indices of the individual chronologies. Positive values of the analyses carried out inform about simultaneous increase of the annual growth width and the climatic parameters (temperature and precipitation), whereas negative ones – about the decrease of value of the climate conditions at the simultaneous increase of the annual growth width. The results of the analyses obtained may be also affected by other factors, such as: the type of the settlement, in which the tree populations grew, the distance from the meteorological stations, as well as the lengths of the analysed sequences of both dependent and independent variables (Schweingruber 1993). For the climatic analyses such site and/or object chronologies were selected, which corresponded with their time extents to the available climatic data. They represented not only living trees, but also historical wood, coming from pines and firs growing in the nineteenth and twentieth centuries in Kraków and its environs.

Except for visual comparisons of dendrograms and using computer programs, so-called signature years are of help at dating the sequences. They are such years, in which the majority of the trees develops the annual growth significantly wider or narrower with respect to the previous one (Huber 1970). There are distinguished positive (the tree-ring width is higher than in the previous year) and negative (the tree-ring width is lower than in the previous year) signature years (Zielski and Krąpiec 2004). The criterion of selection of the signature years is 90% convergence in a population of at least ten sequences. Most of the signature years are the negative years. According to Müller-Stoll (1951), they are of higher meaning in the dendrochronology, because such years are explicitly reflecting some extreme climatic phenomena, such as: very frosty winters, hot and dry summers, or late-spring frosts. Some of the signature years are noticeable so firmly that they have been registered at several taxons. An example of such a signature year, a negative one, is 1940 which was noted in Central Europe at the oak, pine, and beech (Zielski and Krąpiec 2004).

## CURRENT STATE OF DENDROCHRONOLOGICAL RESEARCH

Dendrochronology is a relatively young scientific method; its beginnings date back only to the twentieth century. Broad principles of the method were delineated by an

American astronomer A. E. Douglass, regarded as the father of dendrochronology. He also constructed the first absolute chronology for the wood of the yellow pine (*Pinus ponderosa*). In Europe, dendrochronology started to develop after the Second World War in Germany, due to the efforts of Bruno Huber, who modified the methodological assumptions and commenced construction of long, absolute chronologies. One of the first multi-century patterns for dating the oakwood was elaborated at the end of the 1960s. Since that time, absolute tree-ring patterns have been constructed for various species of trees (cf. Baillie 1995).

In the 1970s, a standard was established for the silver fir from Southern Germany, covering the years 820–1970 AD (Becker and Giertz-Siebenlist 1970). More than twenty years later the next absolute fir patterns have been compiled:

– North German chronology, 928-year-long (994-1921 AD) (Heussner 1996),
– Eastern Austria (977–1997 AD) (Liebert *et al.* 1998),
– Czech (1131–1997 AD) (Kyncl and Kyncl 1996, 1998),
– Northern Switzerland (1213–1993 AD) (Hurni and Orcel 1996),
– Southern Switzerland (1238–1993 AD) (Hurni and Orcel 1996).

Parallel to the studies on the fir wood, the research on the pine wood progressed. Several-hundred-year-long chronologies for *Pinus sylvestris* were constructed for:

– Germany (994 – present) (Heussner 1996),
– Gotland (1124–1987 AD) (Bartholin 1987),
– Finland (Northern Lapland) (50–1993 AD) (Lindholm *et al.* 1999),
– Northern Fennoscandia (5633 BC – present) (Timonen *et al.* 2006),
– South-East Finland (743–1993 AD) (Lindholm *et al.* 2000),
– North-Western Russia (980–1970 AD) (Kolchin and Bitvinskas 1972),
– Russia (surroundings of Novgorod) (822 – present) (Kolchin 1962, Chernykch 1996).

In Germany, the oldest chronology, reaching the turn of the periods Bølling/Allerød, was constructed on the basis of subfossil pinewood from the vicinities of Warendorf, Reichwalde, the river Danube, Isar, and Günz. The 977-year pattern was dated with the fitting curves method to 12,300–11,350 cal BP (Friedrich *et al.* 1999).

In Poland, the first steps in dendrochronology were made in the 1940s and 1950s. In the 1940s, a meteorologist and climatologist Zinkiewicz conducted the first studies on the dependence of the annual growths on the climatic variations (Zinkiewicz 1946). Several years later Ermich examined the influence of the climate conditions on growth of the oak and pine (Ermich 1953, 1959). In the 1960s and 1970s the first efforts of dating historical wood from archaeological excavations were undertaken, e.g. in Szczecin (Gorczyński *et al.* 1965), Opole (Dąbrowski and Ciuk 1972), and Lublin (Dąbrowski *et al.* 1975), however, without unequivocal results. Intense development of the dendrochronology came only in the second half of the 1980s, which was connected with the establishment of new dendrochronological laboratories (ASP in Warsaw, UMK in Toruń, AGH in Kraków, PŚ in Gliwice, AR in Kraków) and with availability of right instrumentation. This quickly resulted in construction of long, absolutely dated standards for the oak, pine, and fir.

Several absolutely dated standards were constructed for the oakwood:

- the Odra River valley in the surroundings of Racibórz – compiled on the basis of subfossil oaks at the Institute of Physics, Silesian University of Technology, by T. Goslar, embracing the period 413–735 AD (Goslar 1987);
- Eastern Pomerania – constructed by T. Ważny at the Hamburg University, and at the ASP in Warsaw, covering the years 996–1985 AD (Ważny 1990);
- Southern Poland (subfossil oaks) – constructed by M. Krąpiec at the Dendrochronological Laboratory of the Faculty of Geology, Geophysics and Environmental Protection AGH – UST in Kraków, of the extent 1795–612 BC and 474 BC – 1555 AD (Krąpiec 1996, 2001; cf. also Krawczyk and Krąpiec 1999);
- Małopolska (910–1997 AD), Lower Silesia (780–1994 AD), and Wielkopolska (449–1994 AD) – constructed at the Dendrochronological Laboratory of the Faculty of Geology, Geophysics and Environmental Protection AGH – UST (Krąpiec 1998).

The first Polish several-hundred-year-long standard chronology for the pinewood from the Vistula-Valley Pomerania (Pomorze Nadwiślańskie), absolutely dated (1106–1994 AD), was elaborated at the Dendrochronological Laboratory UMK in Toruń (Zielski 1997). In this Laboratory, several next pine standards were constructed for other regions of Northern Poland: Mazury (1724–1830 AD and 1879–1999 AD) (Zielski, pers. comm.) and Eastern Wielkopolska (1153-1700 AD and 1786–2006 AD) (Zielski, pers. comm.).

The second laboratory, in which the research on construction of multi-century standards for the coniferous tree species is going on is the AGH – UST Laboratory in Kraków. Here, several regional standards for the pine and fir wood were produced. On the basis of the pine wood:

- the Małopolska standard, covering the years 1622–1996 AD (Szychowska-Krąpiec 1997a), and
- the regional chronology for NE Poland, 487-year long (1518–2004 AD) (Szychowska-Krąpiec and Krąpiec 2006) were constructed.

For the fir wood, the regional chronology for Southern Poland was constructed, covering the years 1106–1998 AD (Szychowska-Krąpiec 2000).

The chronologies presented above have frequently been applied to dating secular and sacral structures of wooden historic objects (Krąpiec *et al.* 2006), casings of the mining excavations in the mines (Szychowska-Krąpiec 2003a,b, 2007), as well as wooden artefacts in the archaeological excavations (Krąpiec *et al.* 2006).

At the same time, dendroclimatological studies have been dynamically developed, aiming at the relations between the annual growth and the climate at various species of trees. A new stage of the dendroclimatical research was initiated by the studies of E. Feliksik and Z. Bednarz. In the dendrochronological laboratory at the Agricultural University in Kraków, the relations annual growth – climate at the fir were investigated by Feliksik (1986, 1990), and at the arolla pine (*Pinus cembra*), common spruce (*Picea abies*), and oak (*Quercus sp.*) by Bednarz (1976, 1987, Bednarz and Niedźwiedź 1997).

Dendroclimatology of the Scots pine (*Pinus sylvestris*) from selected sites in Poland was studied by Wilczyński (1999, Wilczyński *et al.* 2001). This author also carried out dendroclimatical research on populations of the pine trees growing in the mountains: in the Sudetes (Wilczyński and Skrzyszewski 2002a, 2003) and in the Carpatians (Wilczyński and Skrzyszewski 2002b). On the basis of the relation climate – annual growth in the Carpatians, three dendroclimatical regions of the Scots pine have been distinguished (Wilczyński 2005). Outside Poland, the studies aiming at reconstruction of the main climate elements, i.e. the air temperature and rainfall, on the basis of the annual-growth sequences were conducted, among others in: the United States (Stahle and Cleaveland 1994), Mexico (Diaz *et al.* 2001), Russia (Shiyatov 1995, Naurzbaev and Vaganov 2000), South America (Villalba *et al.* 1996), China (Zhu *et al.* 2009), India (Yadav *et al.* 1999), Japan (Kobayashi *et al.* 1998), Korea (Park and Yadav 1998), New Zealand (D'Arrigo *et al.* 1998), Tasmania (Cook *et al.* 1996), Morocco (Meko 1985), South Africa (Stahle *et al.* 1997), and the Middle East (Touchan *et al.* 1999). Also in Europe, the reconstructions of the climate in the past millennium were attempted, among others in: the Czech Republic (Brazdil *et al.* 2002), Finland (Lindholm *et al.* 1999, Helama *et al.* 2004), Germany (Friedrich *et al.* 1999, Wilson *et al.* 2005), Turkey (Akkemik *et al.* 2005), and Slovenia (Čufar *et al.* 2008).

In the last years an important aspect of the dendroclimatical studies consists in attempts of reconstruction of the climate on the basis of the sequences of the annual growths at trees, mainly reconstruction of the thermal conditions and the rainfall in the vegetation season. For this purpose, long oak chronologies are being used, e.g. in Slovenia, for reconstruction of the dry and humid summer periods in the last 500 years (Čufar *et al.* 2008), or spruce chronologies, on the basis of which attempts of reconstruction of the rainfall in the months March-August in Bavaria have been undertaken (Wilson *et al.* 2005). More than 1000-year-long pine chronologies from North-Eastern Lapland were used for reconstruction of the climate in Northern Finland (Helama *et al.* 2004).

Beside dendroclimatology, the dendroecological studies have been conducted since the 1990s. The Scots pine and silver fir are the species often used in monitoring of the industrial pollutions, as the sources of the record of the temporal extent and impact of the pollutants on the tree stands. One of the first studies of this type was the analysis of the annual growth sequences at the Scots pine in the surroundings of Puławy, carried out by Oleksyn (Oleksyn *et al.* 1993). Such investigations were also applied to the monitoring of the pine tree stands in the North of Poland:

- the pine tree stands neighbouring the Paper and Cellulose Plant in Kwidzyn (Zielski 1992),
- the Primeval Forest 'Puszcza Wkrzańska', where the negative influence of the Chemical Plants 'Police' on the neighbouring tree stands of the primeval forest was determined (Szychowska-Krąpiec and Wiśniowski 1996).

In southern Poland, the dendroecological monitoring of the tree stands was carried out to a considerably wider extent, among others in:

– the Primeval Forest ‘Puszcza Niepołomicka’ (Szychowska-Krąpiec 1997b),
– the Ojców National Park (Krąpiec and Szychowska-Krąpiec 2001),
– the tree stands of the Krakowsko-Częstochowska Upland (Danek 2007),
– the Holy Cross (Świętokrzyski) National Park (Podlaski 2002),
– the Kielce Upland (Wertz 2009),
– the Sudetes (Wilczyński 2006).

The tree stands growing in the surroundings of the pollution emitters, exposed to the stress, demonstrated reductions of widths of the annual growths lasting several years, with intensification in the 1970s and 1980s. In particularly drastic cases, the growth rings were not only reduced, but even faded and/or vanished in a part of the trunk, or did not develop at all in a given vegetation season.

Within the last 100 years huge progress has been made in dendrochronology. The tree-ring dating found application in a row of the fields of science, e.g. in archaeology, art history, climatology, and stratigraphy. Contemporary dendrochronology is a widely comprehended term, embracing such aspects, as: dendroarchaeology, dendroclimatology, dendroecology, dendrohydrology, dendrogeomorphology, dendroglaciology, and dendrovolcanology.

## NEW REGIONAL CHRONOLOGIES FOR THE MAŁOPOLSKA REGION (research sites, local chronologies)

Dendrochronological dating is based on absolutely dated standards (chronologies). Unfortunately, such standards, constructed individually for every tree taxon, have a limited territorial extent. Therefore, effective and successful application of this method requires a chronology produced from trees growing in the same area, climatically cohesive. Another essential factor is the length of the chronology, i.e. its extent on the time scale. The further back into historical times the chronology is reaching, the more precious dating tool it is. Construction of a thousand-year standard is, however, very laborious and time-consuming, taking several years of arduous research.

### Pine standard

The pine chronology was produced from 238 samples representing, among others, historical wood from roof structures of 14 churches situated in the Świętokrzyskie and Małopolskie voivodeships and three secular objects from Kraków and Chudów. Historical wood, which also came from wooden casings of the salt mines in Wieliczka and Bochnia, was supplemented by wooden elements excavated at three archaeological sites in Kraków and its surroundings. The chronology was lengthened till the present thanks to samples of living trees from five sites: Krzeszowice, Chrzanów, two sites in the Niepołomice Forest, and the Nowy Targ Forests. The highest percentage participation (38.3%) is made by wood representing architectural objects, a little bit less by wood from the salt mines (26%) and from living trees (24.8%), and the least amount of wood came from the archaeological excavations (10.9%). The location of the sampling and research sites is presented in Fig. 1. The oldest part of the standard is formed by samples of wood explored from the archaeological excavations in Kraków (the Central Market Square and the Barbican) and Zakrzowiec, the younger one – by samples from the architectural objects, and the youngest interval – by samples taken from living trees. The sampling and research sites, together with the corresponding object and/or site chronologies, are briefly presented and discussed below.

### Kraków, Central Market Square

Archaeological excavations on the Central Market Square in Kraków were undertaken in 2004, at the reconstruction of the pavement plates west from the Cloth Hall (Sukiennice), at the site of the ancient Shoemaker's Stalls, red gravediggers' stalls, Gothic houses, the mediaeval and Renaissance Town Hall, and other buildings (Zaitz 2006). Various wooden structures, better or worse preserved, were came across during that research, lasting till 2006. These were fragments of beams, planks or boards, which could be remains of foundations of frame-construction wooden buildings, elements of mobile stalls and/or stores, fragments of the pavement kerbs, and elements of wells and water pipes (Zaitz 2006). Wherever it was possible, samples were taken for the dendrochronological analysis. Preliminary results of the first analyses of a dozen or so pine samples were published by Krąpiec *et al.* (2006). Altogether, over 80 samples of the pine wood were analysed. On the basis of the best mutually correlating samples, the object chronology was constructed, covering the years 1091–1345 AD. It was produced from 18 individual sequences; the longest of them counted 198 growth rings, and the shortest one – 46 rings. In the case of five samples the presence of the last growth ring was stated. The oldest samples with the last rings preserved came from the pine trees cut down in the 1280s, and the youngest ones – in 1308 and 1309 (Fig. 2). Having analysed the presence of the last rings, it was possible to distinguish the phases of introducing timbers into wooden structures on the Central Market Square in Kraków. The first phase took place in the years 1283–1288, and the next ones in 1300 and 1308–9. The phases of introducing wood into the existing structures were probably bound with their reconstruction and/or repair.

### Zakrzowiec, well

In 2006, at the archaeological excavations led on the route of the future motorway A-4 (Kraków – Tarnów) in Zakrzowiec (Niepołomice common), in the site no 6, a well was encountered, of which twelve wooden elements, in the form of planks, were handed over for the dendrochronological analysis. Among these twelve samples, five represented the wood of the Scots pine. Individual sequences were relatively short; they contained from 37 to 51 rings. In none of them the last growth ring was preserved. Based on four patterns, the 51-year object chronology was constructed, covering the years 1167–1217 AD (Fig. 3). Because of lack of the last rings, one could only suppose that the well was made in the 1230s or 1240s.

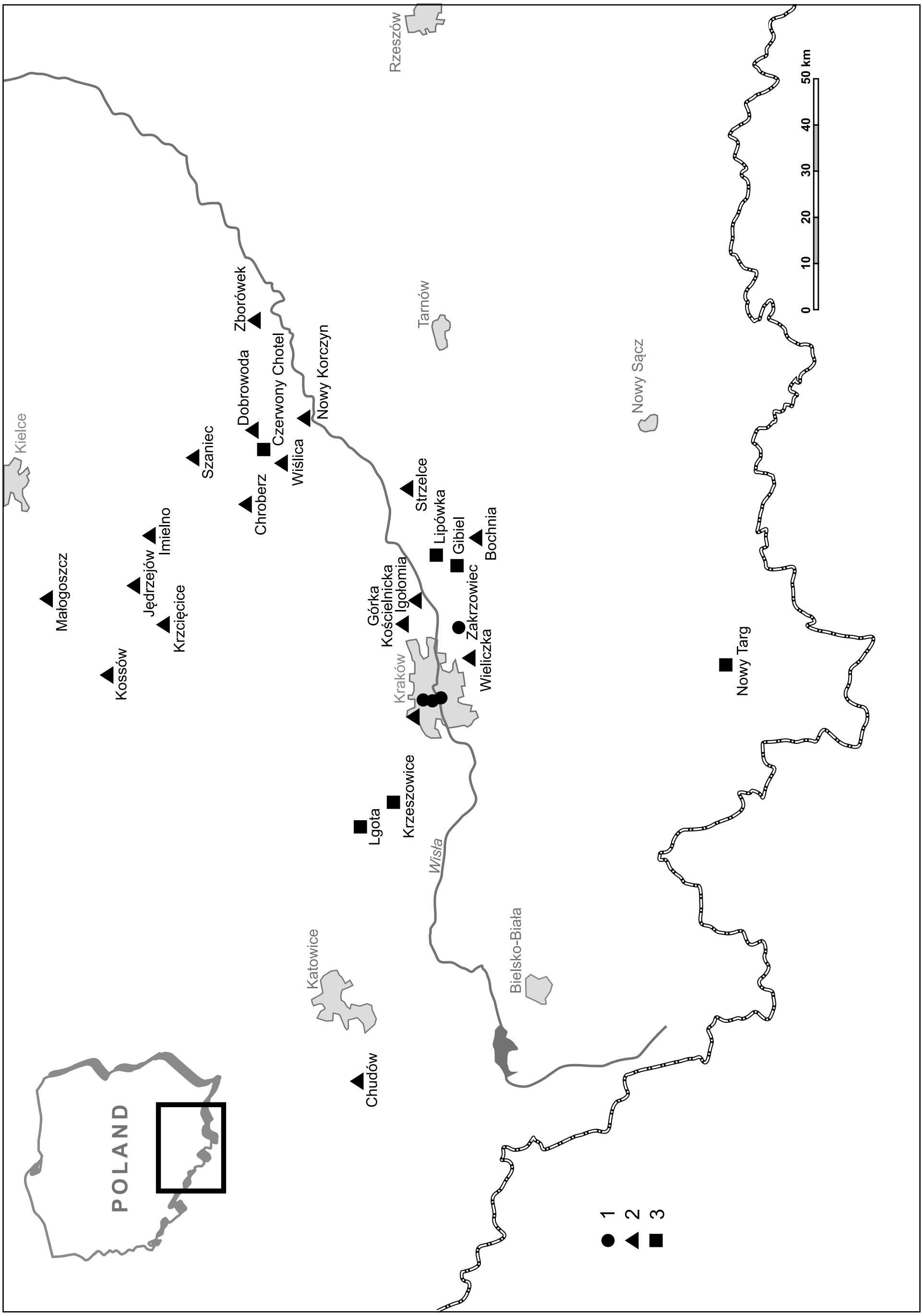


Fig. 1. Location of sampling sites of the pine wood: 1 – wood from archaeological excavations, 2 – wood from architectural objects, 3 – samples from living trees

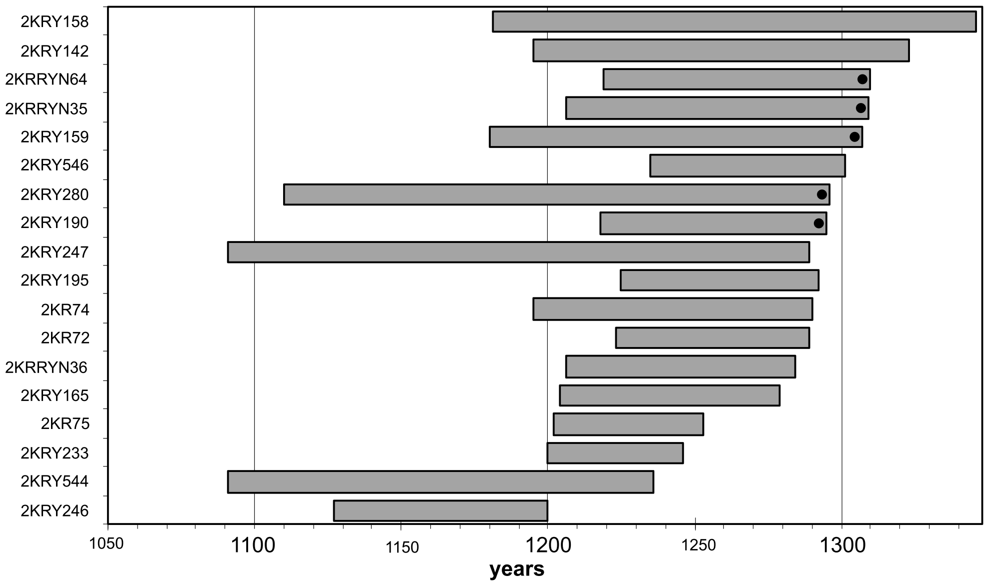


Fig. 2. Dendrochronological sequences forming the local chronology 2KRR_1, spanning the years 1091–1345. The last growth ring marked with dot

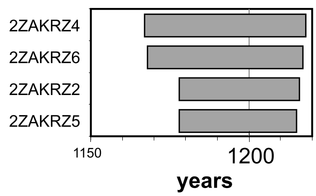


Fig. 3. Correlation diagram of growth sequences sampled from the well in Zakrzowiec

## Kraków, Barbican

In 1994 the excavation works were carried in the Barbican in Kraków. During these works timber structures were encountered, from which 15 samples in form of slices and wedges were taken for the dendrochronological analysis. Four samples represented the pine wood. The analysed sequences contained from 66 to 97 growths, unfortunately, in none of them the last growth ring was preserved. On this basis, the 97-year site chronology was constructed, covering the years 1195–1291 AD (Fig. 4). Lack of the last, youngest growths does not allow to date the examined structures with one-year accuracy; it is only possible to state that they were made from pine trees cut down at the turn of the thirteenth and fourteenth centuries.

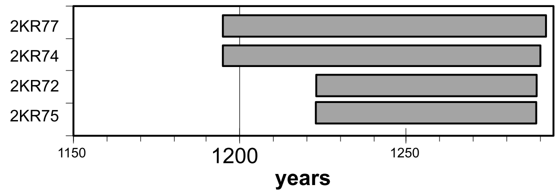


Fig. 4. Correlation diagram of growth sequences sampled from Barbican in Kraków

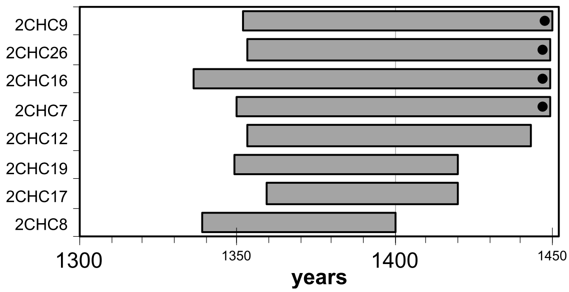


Fig. 5. Correlation diagram of growth sequences sampled from the church in Chotel Czerwony. The last growth rings marked with dots

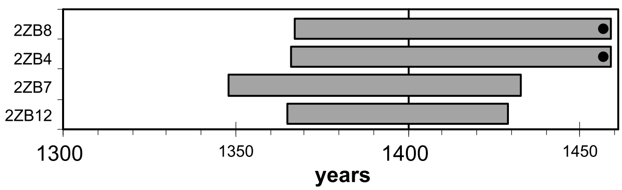


Fig. 6. Dendrochronological dating of growth sequences sampled from the church in Zborówek. The last growth rings marked with dots

The timbers encountered at the archaeological excavations were used for construction of the older part of the pine chronology, spanning the years 1091–1345 AD. Its younger part was compiled on the basis of samples taken from wooden structures of various objects; among others several churches from the Świętokrzyskie voivodeship. They proved to contain pine wood from various times, which allowed to extend the chronology till 1827 AD.

## Chotel Czerwony, church

The Gothic Church of St. Bartholomew Apostle in Chotel Czerwony (Busko county) was founded by Jan Długosz and built of stone in the years 1440–1450. It is composed of the square nave, the narrower chancel, and two porches added to the nave. The church is covered with high, gable roofs (Mroczko and Arszyński, 1995). In the 1990s, renovation of the church took place, during which the roof structure was partly replaced and refurbished. From these wooden structures of the roof, beams over the nave and the chancel, 27 samples in the form of cores and slices were taken for analyses. All samples represented the wood of the Scots pine and the individual sequences contained from 42 to 114 increments. Based on eight best correlating sequences, the object chronology was constructed; 114 years in length and spanning the years 1336–1449 AD. In four samples the last growth ring was retained, what enabled exact determination of the years of felling the pine trees for construction of the roof to 1449 AD (Fig. 5). This, in turn, allows to conclude that the roof structure of the church in Chotel Czerwony dates back to the time of its construction.

### Zborówek, church

The parish church dedicated to St. Idzi in Zborówek (Busko county) is one of the oldest, incontestably dated, wooden churches in Poland. It is a wooden, late-Gothic church of the framework structure, built in 1459 (Faryna-Paszkiewicz *et al*. 2001). In 1908 the brick, neo-Romanesque nave was added. The wooden part consists of the nave and the chancel closed from three sides, by which the sacristy was added from the northern side. At present, it constitutes the chancel of the new church (Mroczko and Arszyński 1995). From the roof structure above the older part of the church, 17 samples in the form of cores were collected. They came from, among others, beams and rafters, three of them represented the oakwood, and the remaining ones – pine. The individual sequences of the pine samples contained from 41 into 97 growth rings. Based on four sequences, mutually best correlating, the average curve of the object was produced, covering the years 1348–1458 AD. In two samples the youngest growth ring was detected, which allowed for the exact dating of cutting down the pine trees, of which the structural elements of the roof were made, to 1458 (Fig. 6). Thus, the roof structure of the late-Gothic church in Zborówek dates back to the time of its building.

### Chroberz, church

The church of the Assumption of Lady Mary and of St. Jan Kanty in Chroberz (Pińczów county). The parish in Chroberz existed already in the twelfth century and the information about the church dates back to around 1326. The present, Gothic-Renaissance church was built around 1550, thanks to foundation of Stanisław Tarnowski, the Zawichost castellan. It is a stone, single-nave church (Faryna-Paszkiewicz *et al.* 2001). Eleven samples for analyses were taken from the roof structure above the nave of the church. All but one samples represented the wood of the Scots pine, the one exception was fir. The lengths of the individual sequences were highly diversified, from 25 up to 164 growth rings. The fir sample consisted of 68 increments. Dendrochronological dating showed that the pine wood from which the structural elements were made came from the trees cut down in 1429 (presence of the last growth ring) (Fig. 7).

The pine sequence covers the period 1257–1429 AD. The element made of fir wood is younger, it came from the fir tree cut down in 1547; since the sample retained the last growth, the time of cutting the tree down could be determined with one-year accuracy. This fir timber is apparently contemporary to the time of construction of the church, which was built at the end of the1540s. The pine elements of the structure were most probably re-used at its construction.

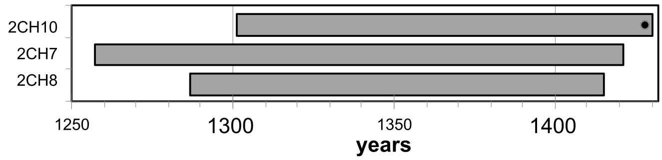


Fig. 7. Dendrochronological dating of growth sequences sampled from the church in Chroberz

W i ś l i c a ,  c h u r c h

The collegiate church of Birth of Our Lady Mary in Wiślica (Busko county). The biggest Gothic church in the Holy Cross (Świętokrzyski) region was constructed by the king Kazimierz the Great in the third quarter of the fourteenth century. It was slightly rebuilt about 1450–1464 (Faryna-Paszkiewicz *et al.* 2001). The samples for analyses were taken in the form of slices and cores from the roof structure of the collegiate-church nave. Altogether, 15 elements were sampled. They represented the wood of two species: the Scots pine and the silver fir. On the basis of the pine samples the 105-year chronology was produced, covering the years 1339–1443 AD (Fig. 8). Thanks to dendrochronological dating it is possible to state that the roof structure contains timbers coming from the first half of the fifteenth century, which was probably introduced there during the renovation.

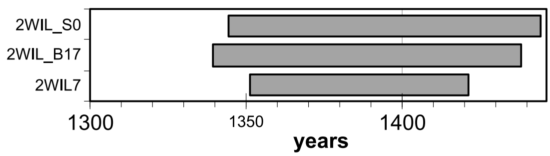


Fig. 8. Correlation diagram of growth sequences sampled from the church in Wiślica

I m i e l n o ,  c h u r c h

The St. Nicholas Church in Imielno (Jędrzejów county) is a stony church built in the thirteenth century. Thoroughly rebuilt in the fifteenth and seventeenth centuries, at present it represents the Romanesque style with Gothic and Baroque elements (Faryna-Paszkiewicz *et al.* 2001). From the roof structure eight samples were taken for analyses.

All represented the wood of the Scots pine. Most of the sampled elements could not yield complete cores with the last rings, because the wood was destroyed by the wood-eaters. Only one sample retained the last, youngest ring. Individual sequences contained from 38 to 104 growth rings. Based on five mutually best correlating patterns, the object chronology was constructed – counting 125 years and covering the period 1457–1581 AD (Fig. 9). Thanks to the presence of the last ring it was possible to determine the exact date of cutting down the pine trees, from which the elements of the structure were made for 1581 AD, and the time of its construction for the beginning of the 1580s.

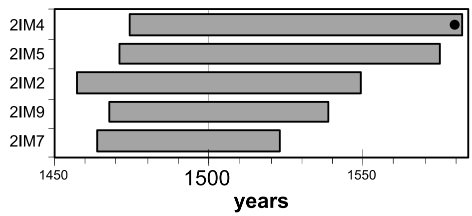


Fig. 9. Dendrochronological dating of growth sequences sampled from the church in Imielno. The last growth ring marked with dot

## Krzcięcice, church

The parish church of St. Prokop in Krzcięcice (Jędrzejów county) was funded in the years 1531–1542. It is a late-Gothic, single-nave church, built from bricks and blocks of sandstone (Faryna-Paszkiewicz *et al.* 2001). At the sides of the nave two chapels appear and at the front a large porch is present. The wood of the roof structure above the nave and the chancel was subjected to the analysis; altogether 22 elements were sampled. All samples represented the wood of the Scots pine. The length of the individual sequences was diversified from 29 to 109 growth rings, in two cases the last rings were preserved. On the basis of 15 mutually best correlating samples, the 115-year average pattern was established. It was absolutely dated to the years 1424–538 AD. The presence of the last growths in the sequences permits to state that pines from which the structural elements of the roof were made were cut down in 1538 AD (Fig. 10). The roof structure, made at the end of the 1530s, dates back to the time of construction of the church.

## Szaniec, church

Gothic church of the Assumption of Our Lady Mary in Szaniec (Busko county) was most probably built in 1499. It is a two-nave church with a chapel from the north side. At the beginning of the twentieth century it was restored (Faryna-Paszkiewicz *et al.* 2001). The church is covered with a steep, sloping roof. For the dendrochronological analysis 26 samples from elements of the roof structure were taken. All represented the wood of the Scots pine. Their individual sequences counted from 28 to 107 growth rings. On the basis of six mutually best correlating patterns, the 128-year average curve was constructed and dendrochronologically dated to the years 1530–1657 AD. Thanks to presence of the last ring, cutting down the pine tree from which the elements of the roof structure were made could be exactly dated to 1657 AD (Fig. 11). In spite of the fact that the walls of the church date back to the end of the fifteenth century, the roof structure is younger; it was probably replaced after the Polish-Swedish war.

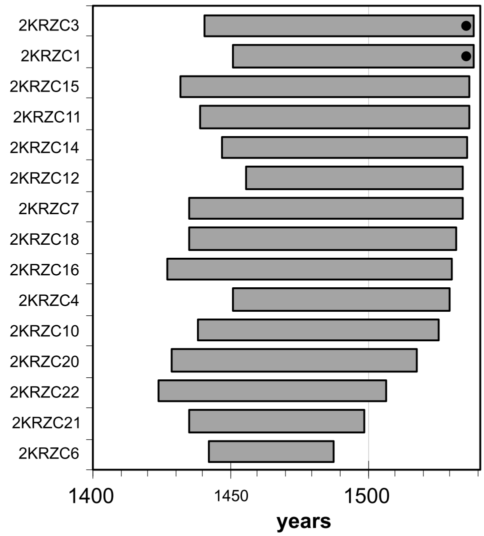


Fig. 10. Correlation diagram of growth sequences sampled from the church in Krzcięcice. The last growth rings marked with dots

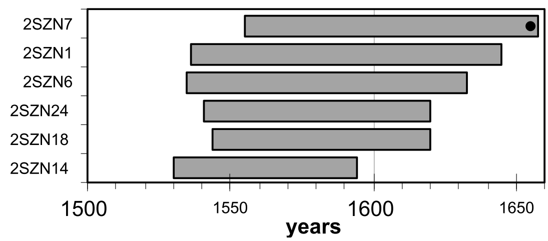


Fig. 11. Dendrochronological dating of growth sequences sampled from the church in Szaniec. The last growth ring marked with dot

## Kossów, church

The Church of the God's Mother from Częstochowa in Kossów (Włoszczowa county) is a small, single-nave wooden object of the framework structure, probably raised in the mid-seventeenth century (Faryna-Paszkiewicz *et al.* 2001). It was most probably built at the site of an earlier, fifteenth-century church (Mirowski 2005). In the last century it was twice renovated, in 1937 and in 1958. The church is oriented, and the roof is covered with shingles. From structural elements of the roof 13 samples were taken, all of them represented pine wood. Individual sequences consisted of various numbers of growths, from 31 to 158; four of them were complete and contained the last rings. On the base of seven mutually correlating individual curves the object chronology was constructed. It counts 178 years and covers the period 1599–1776 AD. The last growth rings, present in three sequences, allowed to determine the accurate date of cutting the pine trees down to 1692. However, the roof structure contains younger elements as well, coming from pines cut down in the 1740s (1738 AD) and in the 1780s (1776 AD) (Fig. 12).

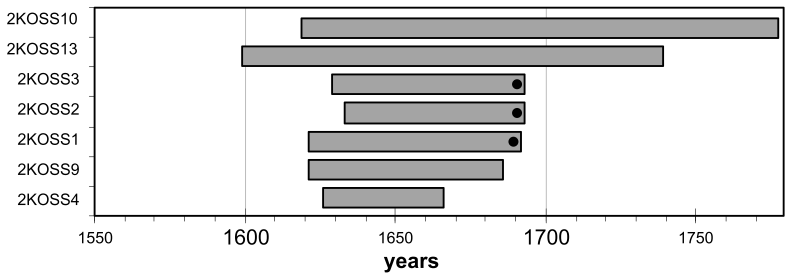


Fig. 12. Correlation diagram of growth sequences sampled from the church in Kossów. The last growth ring marked with dot

The opinions on the date of construction of the church are quite divergent, the difference reaching as many as about 150 years. According to FARYNA-PASZKIEWICZ *et al.* (2001), it was built in the first half of the seventeenth century, whereas according to WITANOWSKI (2001) – in 1764 by Józefina Michałowska. The analyses carried out did not reveal the presence of wood from the first half of the seventeenth century. The oldest wood originates from the end of the seventeenth century. Perhaps it came from the burnt church standing there before and was re-used at building the church by Józefina Michałowska in 1764. The wood coming from the youngest pines, cut in the 1770s, could be connected with repairs of the roof structure.

### Małogoszcz, church

The church of the Assumption of Our Lady Mary in Małogoszcz (Jędrzejów county) was built in place of an old wooden church in the years 1591–1595. It was built on the plan of the elongated rectangle in the late-Renaissance style. The single-nave church (FARYNA-PASZKIEWICZ *et al.* 2001) was thoroughly rebuilt in the years 1796–1800. From elements of the roof structure, 15 samples in the form of cores were collected. All represented the wood of the Scots pine. Individual sequences contained low figures of growths, from 26 to 63 ones. On the basis of two best fitting sequences, the object chronology was constructed, counting 70 years and covering the period 1589–1658 AD. The wood appearing in the roof structure came from pines cut down in the second half of the seventeenth century and it was probably introduced there in the time of repair or reconstruction of the church.

Dobrowoda, church

The church of St. Magdalene in Dobrowoda (Busko county), dating back to 1354, was rebuilt in the late-Gothic style in the years 1524–1525. Built from the blocks of stone, it is a single-nave church with somewhat narrower and lower chancel (Faryna-Paszkiewicz *et al.* 2001). For the analyses seven samples were taken in the form of cores from beams, joists, and a rafter of the roof structure. All samples represented the wood of the Scots pine. In the majority of the sampled elements the complete core with the last rings could not be gained, because of the sapwood damages made by the wood-eaters. Individual sequences contained from 66 to 87 increments. The average pattern established for this object was dated to 1634–1762 AD (Fig. 13). The analysed roof structure dates back to the early 1760s and/or 1770s, so it is considerably younger than the walls of the church.

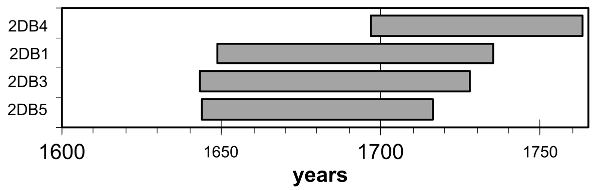


Fig. 13. Dendrochronological dating of growth sequences sampled from the church in Dobrowoda

Nowy Korczyn, church

The church of St. Trinity in Nowy Korczyn (Busko county) was built before 1585. It is a stony, single-nave church, which Gothic-Renaissance appearance gained after the reconstruction in the years 1610–1634 (Faryna-Paszkiewicz *et al.* 2001). High gable roofs cover the church. From wood of the roof structure nine samples were taken, all representing the wood of the Scots pine. Individual sequences of the samples measured contained from 48 to 111 growths, only in one sample the last growth was preserved. On the basis of three sequences the object chronology, covering the years 1653–1776 AD, was constructed (Fig. 14). The last growth ring preserved allows to state that the wood appearing in the roof structure came from pines cut down in 1776 AD. The roof structure is younger than walls of the church, which is probably bound with its changing or renovation.


Fig. 14. Correlation diagram of growth sequences sampled from the church in Nowy Korczyn. The last growth ring marked with dot

## Strzelce Wielkie, church

The parish church of St. Sebastian in Strzelce Wielkie (Brzesko county) was built in 1785. It is a wooden boarded and single-nave church, of the framework structure (Kornecki 1999), renovated in 1936. From the roof structure 30 samples were taken, all representing the wood of the Scots pine. Individual sequences contained relatively low numbers of growth rings, from 30 to 90, and were characterized by numerous disturbances, such as zones with very narrow and/or missing rings. The obtained average object curve, counting 62 years, was dated to 1723–1784 AD (Fig. 15). Since in all elements the last growth was preserved, it was possible to set the date of cutting the pine trees, from which wood the roof structure was made, with the accuracy of one year. The roof structure of the church in Strzelce Wielkie dates back to the time of the construction of this church.

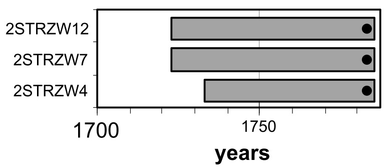


Fig. 15. Dendrochronological dating of growth sequences sampled from the church in Strzelce Wielkie. The last growth rings marked with dots

## Górka Kościelnicka, church

On the outskirts of Kraków, at Górka Kościelnicka, a wooden, parish church of All Saints is situated. The single-nave church, of the framework structure, was built in 1646. It was several times renovated, among others in 1777 (Brykowski and Kornecki 1984). Samples for the analyses were taken from elements of the roof structure, all representing the wood of the Scots pine. In spite of long individual sequences, from 111 to 142 growths, the last ring was not observed in any of them. On the basis of five mutually best correlating individual sequences, the object chronology was established, covering the years 1545–1689 AD (Fig. 16). The elements of the roof structure at the church in Górka Kościelnicka are about 50 years younger than the walls of the church, which is probably caused by its renovation at the turn of the centuries.

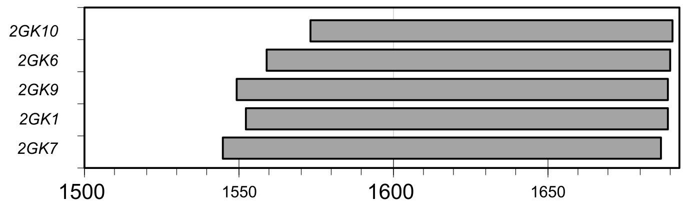


Fig. 16. Correlation diagram of growth sequences sampled from the church in Górka Kościelnicka

Chudów, castle

The castle in Chudów (Gierałtowice common, Silesian voivodeship) was most probably built by J. Gierałtowski in the 1530s. It is an example of a lowland castle, built on a plan close to the rectangle (Chorowska 2003). The castle was subjected to frequent reconstructions; thanks to one of them, carried out by the Foglar family in 1717, it was regarded as one the most wonderful residences in Silesia. After 1768 it started changing owners, losing it meaning and magnificence. In 1837 the castle was reconstructed once more, but in 1875 it was destroyed by the fire, then demolished, and became a ruin (Nocoń 2000). In 1995, the Foundation 'Chudów Castle' was established which is aimed at the reconstruction of the object. At the end of the 1990s, the foundation passed for analyses 20 samples of wood coming from the castle (10) and the granary (10). They represented the wood of oak, pine, and fir. The pine wood came from ceiling beams of the granary, rooms no 1 and 2. Individual sequences contained from 56 to 86 growth rings, two of them were preserved completely, with the last growth rings. Based on four sequences the object curve was established; 91 years in length, embracing the years 1669–1759 AD (Fig. 17). The elements of the ceiling in the room no 2 were made of wood of pine trees cut down in the years 1758 and 1759.

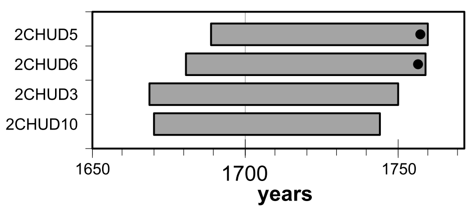


Fig. 17. Dendrochronological dating of growth sequences sampled from the castle in Chudów. The last growth rings marked with dots

Bochnia, salt mine

The Bochnia Salt Mine belongs to the oldest mines in Poland. The mining activity, which begun in the thirteenth century and lasted till the twentieth century, brought about an incessant demand for wood, used for various purposes (transport, building).

Timbers collected during the centuries present a precious store of dendrochronological samples. In 2001–2004, in the framework of the research project no 6 P04D 07721, financed by the Committee for Scientific Research in Poland (KBN), the oldest levels of the mine were dendrochronologically sampled. 202 samples of pine wood were collected from the Danielowiec level (among others, the Gazaris shaft, the Danielowiec gallery, the Floris gallery), the Sobieski level (the Stanetti chambers), the Wernier level (the Śmierdziuchy chamber), the August level (among others the Mysiur stable, the August gallery, the Rabsztyn basket, the Ważyn treadmill), the Podmoście level, the Calvary descent, and the Regis stairs. Samples for the analyses were taken with the Pressler borer, and occasionally with a handsaw. The study resulted in absolute dating of e.g. the door frame of the Passionis chapel and casing in the Mysiur stable (Szychowska-Krąpiec 2003a). Other successfully dated timbers came from, among others, the Regis stairs, the Stanetti chambers, the casing of the Smyczek shaft, the Floris shaft bottom, and the Calvary descent. On the basis of the individual sequences overlapping four site chronologies were compiled. The oldest pattern, produced from three samples, covers the years 1253–1331 AD, the two younger ones encompass the period from the sixteenth till the middle of the eighteenth century (1560–1660 AD – four samples, and 1659–1759 AD – eight samples), and the youngest one – 1715–1847 AD (four samples) (Fig. 18). In spite of such a big number of collected samples, serious problems were encountered at correlation of the individual sequences and the chronology construction, connected with quite frequent growth perturbations and wood damages, as well as relatively short sequences.

### Wieliczka, salt mine

The Wieliczka Salt Mine, like the Bochnia Salt Mine, presents a valuable source of wood originating from various periods of time. During sampling wooden casings on the oldest levels of the mine, 68 samples of pine wood were picked up. The oldest ones, dating back to the end of the seventeenth century, were recognised in the Dusząca chamber, whereas the younger, nineteenth-century wood was stated, among others in the chambers Fortynbark, Mirów, Adamów, and the Koniki gallery (Szychowska-Krąpiec 2003b). On the basis of six mutually best correlating individual sequences, the average curve was produced, dated to 1711–1859 AD (Fig. 19).

### Krzeszowice, forest district

The forest district Krzeszowice is situated about 25 km west of Kraków and consists of two ranges: Alwernia and Krzeszowice, of the total surface of 9,437 ha. It is strongly diversified in terms of the habitat types; as many as 13 types of the forest habitats are noted. The predominating species is the pine, occupying the surface of 5,434.26 ha and constituting 59.7% of the forest mass. Among the naturally preserved flora the mixed forest is predominating. In the area of two forestries, Tenczynek (div. 102 and 108) and Czerna (div. 97, 98, 99), over 130 samples were taken from pine trees with a Pressler borer for dendroecological analyses (Koziarz and Koziarz 2007). Individual sequences of pines, which did not exhibit substantial distortions (missing rings, annual growth rings strongly reduced), were used for constructing of the average pattern embracing the years 1907–2006 AD. The lengths of the individual sequences varied from 46 to 100 growth rings.

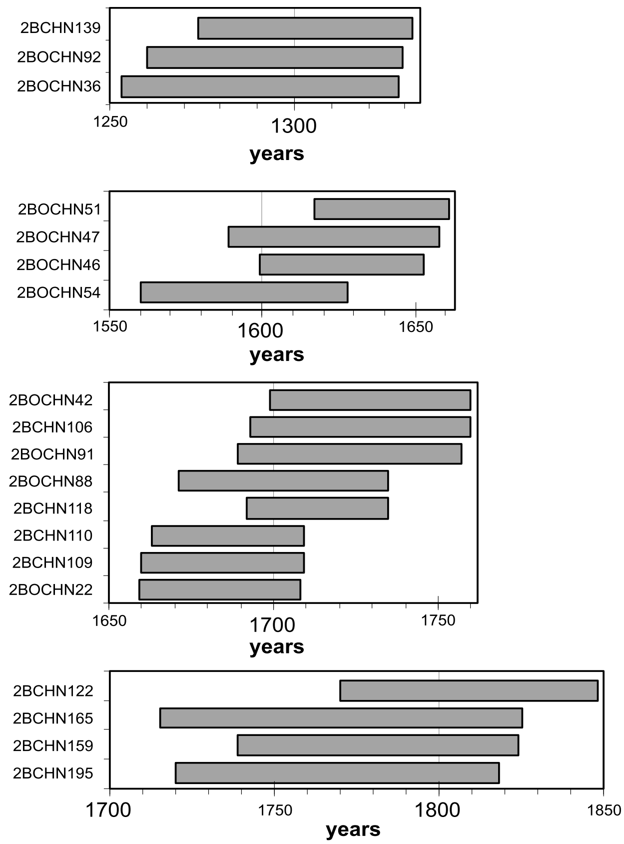


Fig. 18. Correlation diagrams of growth sequences sampled from the Bochnia Salt Mine

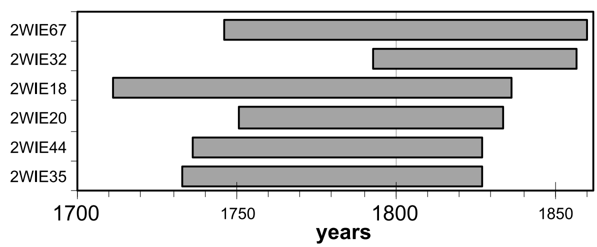


Fig. 19. Dendrochronological dating of growth sequences sampled from the Wieliczka Salt Mine

### Chrzanów, forest district

The Chrzanów forest district (Chrzanów county), situated about 30 km to the west of Kraków, stretches over 20,000 hectares of forests. There were recognised almost all upland and lowland habitats, with the latter prevailing. Forests and mixed forests, which make 74% of all habitats, are predominating. The predominating tree species is the Scots pine, occupying 72.9% of the surface and being the main species in almost all habitats. The average age of the tree stands is 54 years. In 2006, in the forests near Lgota, 154 samples were taken in the form of cores with a Pressler increment borer for dendroecological analyses (Badowska and Kierys 2007). Such ones which did not exhibit reductions in annual growths and/or missing rings were used for construction of the local chronology, spanning the years 1908-2005 AD. It is based on eight individual sequences, containing from 56 to 98 growth rings.

Except for the chronologies described above, the newly constructed pine chronology was produced from some parts of the material which was included in the Małopolska pine standard, covering the years 1622–1996 AD (Szychowska-Krąpiec 1997a). These are the following object chronologies:

- the monastery complex in Jędrzejów 1622–1827 AD,
- the gravedigger's house in Salwator 1740–1822 AD,
- the hospital in Kobierzyn 1820–1956 AD,
- the Sutoris shaft 1760–1905 AD,
- Niepołomice, the Gibiel reserve 1801–1996 AD,
- Niepołomice, the Lipówka reserve 1825–1996 AD,
- the Nowy Targ Forests 1841–1996 AD.

### Jędrzejów, Cistercian monastery complex

In the 1990s the roof structure of the monastery was replaced; from its dismantled fragments 23 samples in the form of slices were collected. In none of them the last ring was preserved. The best correlating individual sequences formed the object chronology, dated to 1622–1827 AD.

### Kraków, Gravedigger's House

During its renovation, from wooden elements of the roof structure eleven pine samples were taken. On the basis of seven individual sequences, the object chronology was constructed, spanning 83 years and dated to 1740–1822 AD.

### Kraków, building of the psychiatric hospital in Kobierzyn

During the renovation of the building no 7, 29 slices were picked up from the replaced roof structure. They represented pine (9) and fir wood (20). The youngest growth rings appeared in three pine samples. On the basis of five samples the average curve was constructed, covering the years 1820–1956 AD.

### Bochnia, salt mine

In the 1990s, the wooden casings of the Sutoris shaft were replaced. The elements of the casings lifted to the surface provided a row of samples to analyses. Altogether, 83 samples in the form of slices were collected. Based on 37 of them, the object chronology was constructed – 146-year in length and covering the period 1760–1905 AD.

### Niepołomice, Gibiel reserve

From old pine trees 37 samples were taken with a Pressler increment borer. On the basis of 22 individual sequences, containing from 80 to 197 growth rings, the average curve was established, which covers the period 1801–1996 AD.

### Niepołomice, Lipówka reserve

For analyses, 25 samples were taken in the form of cores with a Pressler increment borer. The chronology was constructed on the basis of six individual sequences. It counts 172 years and covers the period 1825–1996 AD.

### Nowy Targ Forests (Bory Nowotarskie)

Samples for analyses were taken in divisions 116 and 119 from pine trees growing in a loose complex. 25 pine trees were sampled with a Pressler borer. All of them proved to be over-100-year-old trees. On the basis of 13 individual sequences, mutually best correlating, the site chronology was constructed; counting 156 years and covering the period 1841–1996 AD.

## Characteristics of the pine chronology

The Małopolska chronology is the second such long regional chronology constructed for this tree species in Poland. It was composed of 31 site and object chronologies (Fig. 20), which were mutually correlated and tested with the COFECHA program. Characteristics of the individual components are presented in Table 1. It contains the essential parameters characterizing individual chronologies, such as:

– absolute dating,
– length of the sequence,
– number of samples included in the chronology,
– correlation with the standard (the value *t* and the correlation coefficient *r*),
– average width of the annual growth rings,
– standard deviation,
– autocorrelation,
– mean sensitivity.

Table 1

Characteristics of the local chronologies forming the Małopolska pine standard

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Kraków, Central Market Square, archaeological excavations, wooden structures | 2KRRY_1 | 1091–1345 | 255 | 18 | 0.697 35.270 | 1.25 | 0.571 | 0.855 | 0.166 |
| 2 | Zakrzowiec, archaeological excavations, elements of well | 2ZAK_1 | 1167–1217 | 51 | 4 | 0.545 7.728 | 1.26 | 0.564 | 0.668 | 0.276 |
| 3 | Kraków, Barbican, archaeological excavations, wooden structures | 2KRBA1 | 1195–1291 | 97 | 4 | 0.427 6.613 | 1.38 | 0.555 | 0.732 | 0.261 |
| 4 | Bochnia Salt Mine, wooden casings of mining excavations | 2BOC_1 | 1253–1331 | 79 | 3 | 0.349 7.847 | 2.36 | 1.175 | 0.850 | 0.196 |
| 5 | Chroberz, church, elements of roof structure | 2CHB_1 | 1257–1429 | 173 | 3 | 0.294 7.630 | 1.15 | 0.570 | 0.887 | 0.165 |
| 6 | Chotel Czerwony, church, elements of roof structure | 2CHC_1 | 1336–1449 | 114 | 8 | 0.623 12.796 | 1.78 | 1.027 | 0.928 | 0.125 |
| 7 | Wiślica, church, elements of roof structure | 2WIS_1 | 1339–1443 | 105 | 3 | 0.421 7.527 | 1.46 | 0.647 | 0.896 | 0.166 |
| 8 | Zborówek, church, elements of roof structure | 2ZBR_1 | 1348–1458 | 111 | 4 | 0.620 9.267 | 1.78 | 1.127 | 0.830 | 0.172 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Krzcięcice, church, elements of roof structure | 2KRZC_1 | 1424–1538 | 115 | 15 | 0.671 24.214 | 1.73 | 1.004 | 0.926 | 0.154 |
| 10 | Imielno, church, elements of roof structure | 2IML_1 | 1457–1581 | 125 | 5 | 0.428 5.506 | 1.44 | 0.701 | 0.796 | 0.200 |
| 11 | Szaniec, church, elements of roof structure | 2SZA_1 | 1530–1657 | 128 | 6 | 0.267 11.596 | 2.13 | 1.638 | 0.910 | 0.180 |
| 12 | Kraków, Górka Kościelnicka, church, elements of roof structure | 2GKL_1 | 1545–1689 | 145 | 5 | 0.287 5.159 | 1.07 | 0.778 | 0.967 | 0.137 |
| 13 | Bochnia Salt Mine, wooden casings of mining excavations | 2BOC_2 | 1560–1660 | 101 | 4 | 0.511 8.350 | 2.31 | 0.698 | 704 | 0.187 |
| 14 | Małogoszcz, church, elements of roof structure | 2MAL_1 | 1589–1658 | 70 | 2 | 0.610 6.120 | 3.74 | 1.406 | 0.886 | 0.154 |
| 15 | Kossów, church, elements of roof structure | 2KOS_1 | 1599–1776 | 178 | 7 | 0.219 4.894 | 1.41 | 0.999 | 0.952 | 0.148 |
| 16 | Jędrzejów, monastery, elements of roof structure | 2JDJ_1 | 1622–1827 | 206 | 7 | 0.419 8.574 | 1.24 | 0.956 | 0.945 | 0.179 |
| 17 | Dobrowoda, church, elements of roof structure | 2DOB_1 | 1643–1762 | 120 | 4 | 0.479 6.348 | 2.12 | 0.123 | 0.878 | 0.181 |
| 18 | Nowy Korczyn, church, elements of roof structure | 2NKR_1 | 1653–1776 | 124 | 3 | 0.481 7.129 | 2.16 | 1.681 | 0.961 | 0.178 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | Bochnia Salt Mine, wooden casings of mining excavations | 2BOC_3 | 1659–1759 | 101 | 8 | 0.517 10.842 | 2.45 | 1.061 | 0.851 | 0.205 |
| 20 | Chudów, castle, granary, elements of roof structure | 2CHU_1 | 1669–1759 | 91 | 4 | 0.651 9.796 | 2.07 | 1.392 | 0.863 | 0.226 |
| 21 | Wieliczka Salt Mine, wooden casings of mining excavations | 2WIE_1 | 1711–1859 | 149 | 6 | 0.643 11.571 | 1.88 | 0.972 | 0.822 | 0.185 |
| 22 | Bochnia Salt Mine, wooden casings of mining excavations | 2BOC_4 | 1715–1847 | 133 | 4 | 0.564 8.108 | 1.59 | 0.689 | 0.835 | 0.184 |
| 23 | Strzelce Wielkie, church, elements of roof structure | 2STR_1 | 1723–1784 | 62 | 3 | 0.601 10.031 | 2.75 | 0.870 | 0.661 | 0.218 |
| 24 | Kraków, Gravedigger's House, Salwator, elements of roof structure | 2KDG_1 | 1740–1822 | 83 | 7 | 0.605 10.224 | 2.13 | 1.023 | 0.889 | 0.158 |
| 25 | Bochnia Salt Mine, wooden casings of the Sutoris shaft | 2BOS_1 | 1760–1905 | 146 | 37 | 0.663 25.819 | 2.87 | 1.419 | 0.919 | 0.118 |
| 26 | Niepołomice, Gibiel reserve, living trees | 2NPG_1 | 1801–1997 | 197 | 22 | 0.652 13.137 | 1.82 | 0.720 | 0.855 | 0.165 |
| 27 | Kraków, Kobierzyn, building no 7, elements of roof structure | 2KBZ_1 | 1820–1956 | 137 | 5 | 0.597 8.789 | 2.29 | 1.464 | 0.906 | 0.204 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Auto-correlation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 28 | Niepołomice, Lipówka reserve, living trees | 2NPL_1 | 1825–1996 | 172 | 7 | 0.687 14.868 | 2.21 | 1.678 | 0.930 | 0.185 |
| 29 | Nowy Targ, Bory Nowotarskie, living trees | 2NTG_1 | 1841–1996 | 156 | 13 | 0.472 9.711 | 1.59 | 0.936 | 0.922 | 0.163 |
| 30 | Krzeszowice, forest district, living trees | 2KRZ_1 | 1907–2006 | 100 | 9 | 0.683 9.929 | 1.69 | 0.381 | 0.585 | 0.167 |
| 31 | Chrzanów, forest district, living trees | 2CHR_1 | 1908–2005 | 98 | 8 | 0.628 9.416 | 1.93 | 0.594 | 0.757 | 0.166 |

The average width of the growth rings for all samples included in the standard amounts to 1.8 mm. In comparison to the average width in the North-Polish chronology (2.2 mm), the analysed tree-rings are somewhat narrower. The standard deviation is 0.900, which shows that the course of the standard curve does not display too high amplitudes of changes from year to year. The average autocorrelation value is high (0.863) and significant; hence the analysed time series (standard) cannot be taken as random. The mean sensitivity of the regional chronology is 0.168, which enables to assess the value of the reaction of the trees to the environmental stress. In comparison to the North-Polish chronology (0.182), this sensitivity is lower.

The Małopolska standard consists of 238 individual samples; however, their distribution in individual periods of time is diversified. Fig. 21 presents the replication of the pine chronology. The highest numbers of samples (30 and more) appear in the younger part of the standard from about 1660 till 2006, in particular the nineteenth and twentieth centuries exhibit multiple replication of over 40 samples. The older periods do not display such a broad covering with samples, especially the periods 1320–1350 and 1540–1560, when the number of the samples is significantly lower, below ten. Low covering by the samples in the years 1320–1340 is connected with a change of the research material, i.e. the passage from archaeological wood to historical timbers from wooden objects. The middle of the sixteenth century is a difficult period as to the availability of the pine wood in the Małopolska region and, in spite of numerous attempts to gain more samples, all efforts aimed at the increase of the replication in that period of time failed. The situation is similar in the case of the North-Polish standard chronology, in which that period of time also does not have the replication higher than ten samples. Also, 70 initial years of the Małopolska standard contain less than ten samples, only from 1160 this number increases and reaches almost 20 in the thirteenth century.

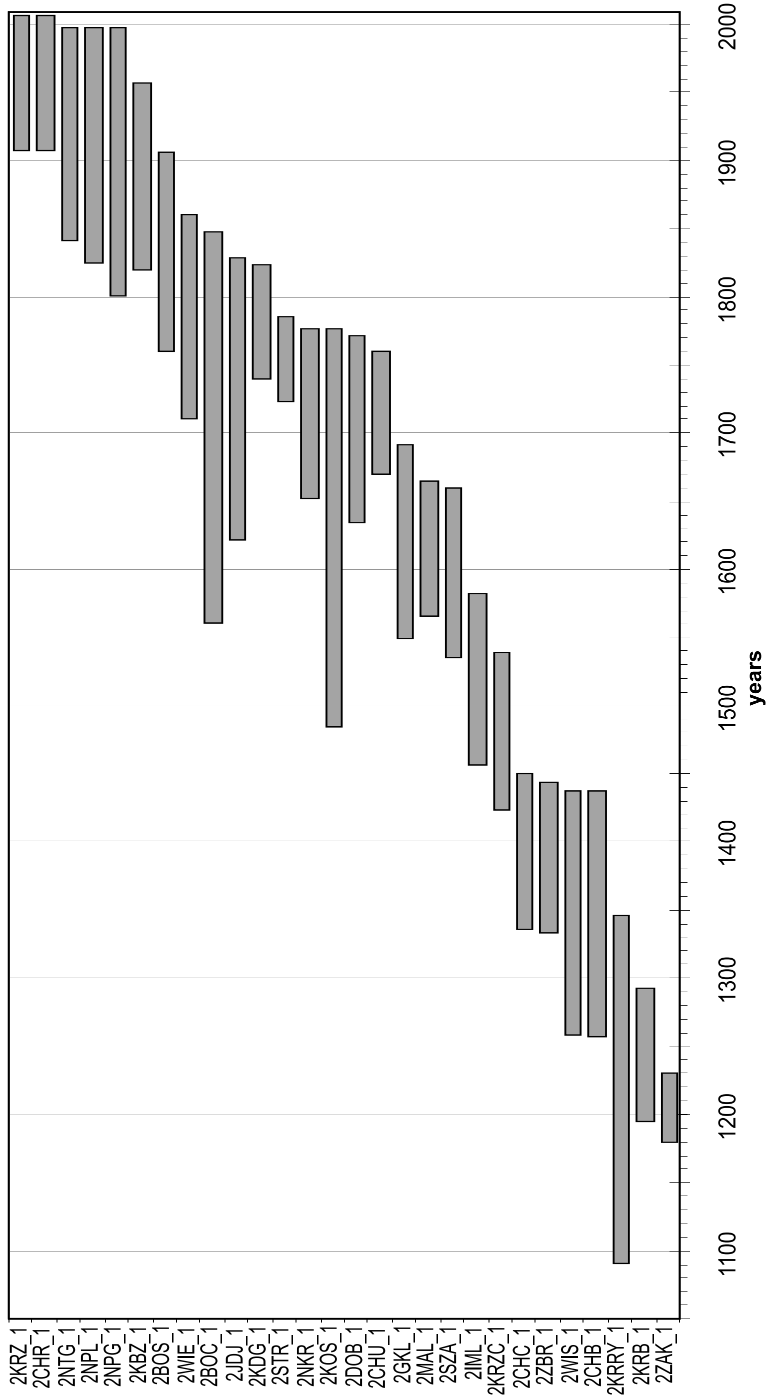


Fig. 20. Local and object chronologies forming the master pine chronology for the Małopolska region, covering the years 1091–2006 AD

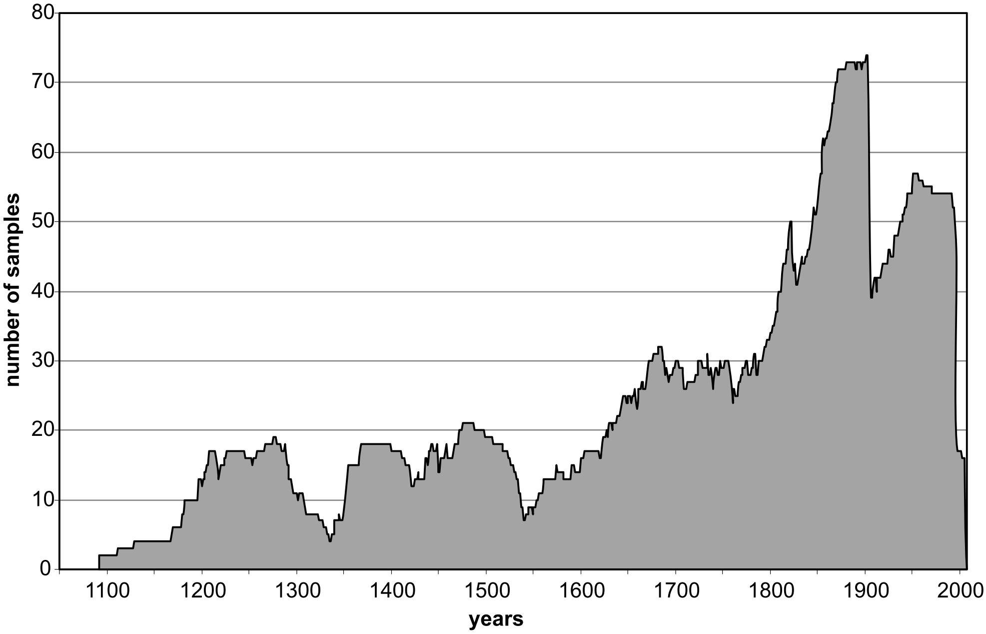


Fig. 21. Replication of the tree-ring sequences in the master pine chronology for the Małopolska region in the period 1091–2006 AD

In the discussed standard, the class of the age of trees, of which samples were included in it, was evaluated as well. There were established 20-year-long ranges. The youngest category consists of the trees with the ages of 50–69 years, the oldest one – the ages of 210–229 years (Fig. 22). The constructed standard contains the least number of samples from old, over 200-year trees (ca. 5%), and the youngest ones, less than 70-year-old, also about 5%. The trees predominating fall into the middle-age range of 70–129 years – about 70%. The samples coming from the trees of the last category are usually characterized with correct development of the tree rings; they are devoid of any senile trends, and the initial, juvenile increments have not any considerable impact on the interpretation of their individual sequences.

## Fir standard

The fir chronology for the Małopolska region, which covers the years 1109–2004 AD, was produced from 560 individual sequences. The oldest part of the chronology was constructed on the basis of historical wood coming from archaeological excavations led in Kraków, Bytom and Hutki. In addition, there was used wood lifted from seven archaeological excavations: Bielsko-Biała, Jaszczurowa, Oświęcim, Rożnów, Rybnik, Wodzisław Śląski, and Wolica. Apart from the archaeological wood, wood appearing in timber structures of secular buildings was used: in Kraków – in St. Wawrzyniec

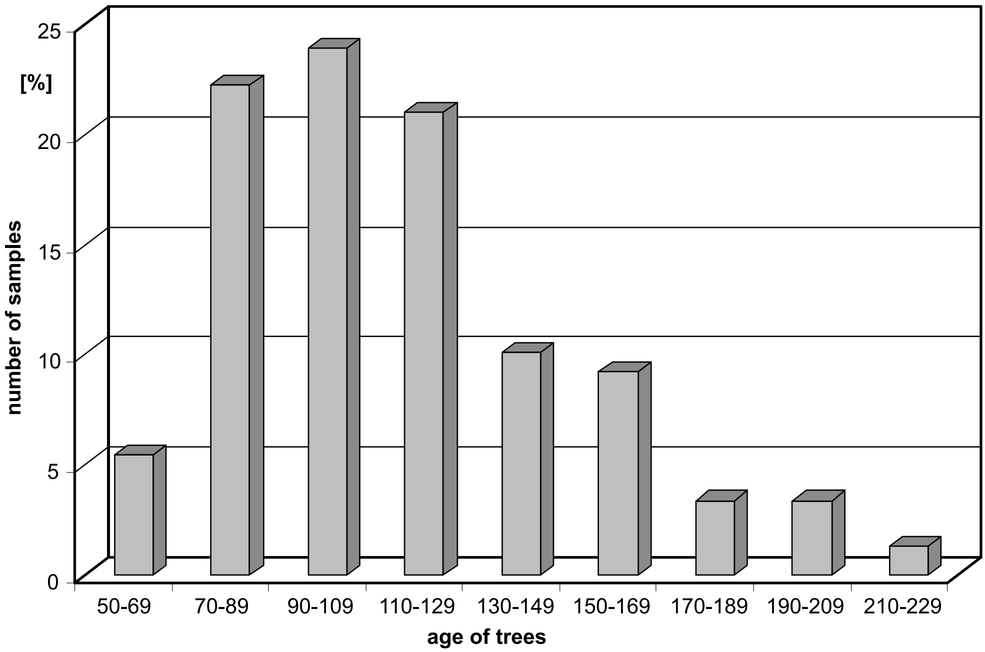


Fig. 22. Percentage parts of the 20-year age ranges of trees forming the Małopolska pine chronology

street, St. Cross (Św. Krzyża) street, Kanonicza street, Grodzka street, Tetmajerówka, UJ (Jagiellonian University) Museum, as well as from the castle in Chudów, the palace in Igołomia, and the churches in Paczółtowice, Wiślica, Wawrzeńczyce, and Grabie. At compiling this standard, samples of wood coming from salt mines in Bochnia and Wieliczka played the crucial role; they provided material representing the period from the thirteenth till the twentieth century. It was extended to the present on the basis of trees growing in the vicinities of Barnowiec, Kąśna, as well as the Ojców and Magurski National Parks. The location of the research sites is presented in Fig. 23.

### Kraków, Central Market Square

This site was exhaustively described at the pine material. Except for the pine wood, 254 samples of fir wood were subjected to the dendrochronological analysis as well. The results of preliminary research were presented by Krąpiec *et al.* (2006). On the basis of 111 individual sequences, mutually best correlating, the 266-year local chronology was established. It covers the period 1109–1374 AD (Fig. 24). The length of the individual sequences was strongly diversified; from 30 to 185 growth rings.

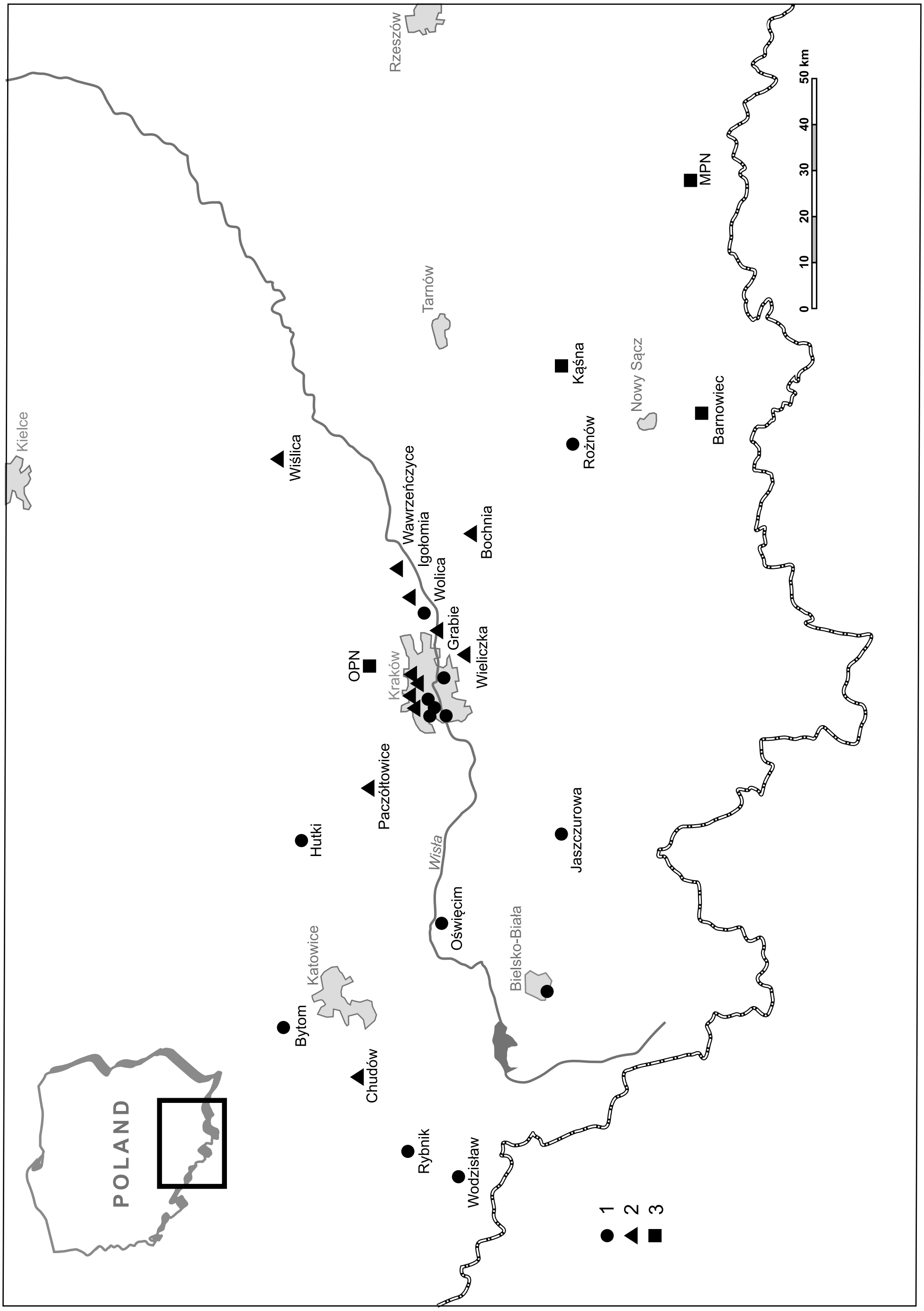


Fig. 23. Location of sampling sites of the fir wood: 1 – wood from archaeological excavations, 2 – wood from architectural objects, 3 – samples from living trees

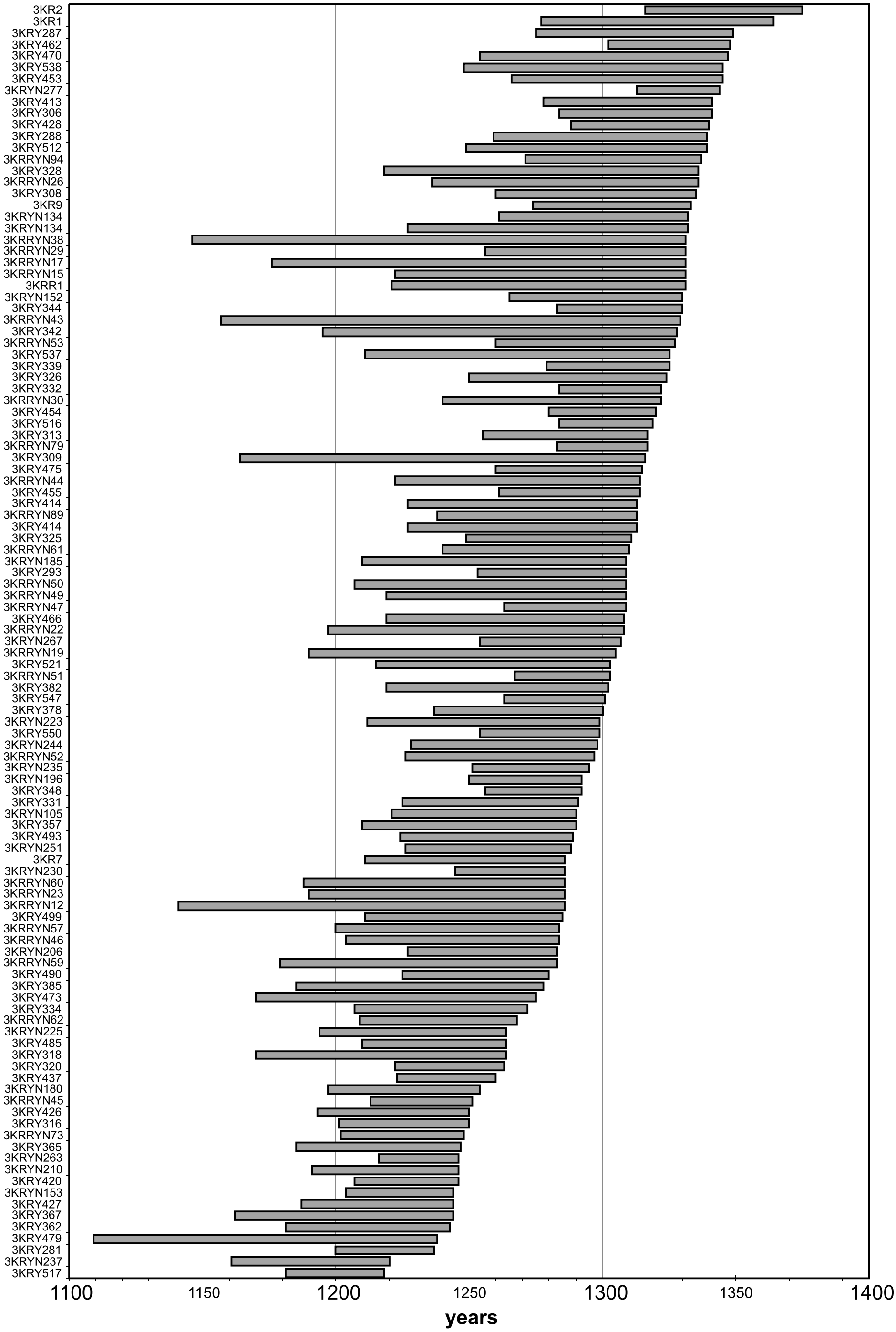


Fig. 24. Correlation diagram of growth sequences sampled from archaeological excavations in the Central Market Square in Kraków

### Rybnik, Old Town

During the archaeological research conducted in the Old Town of Rybnik in 2006, fragments of wood representing the pine, fir, and oak were excavated. Fir wood was represented by 13 elements; structural beams of old, mediaeval buildings. On the basis of six individual sequences, containing from 32 to 103 growth rings and mutually best correlating, the site chronology was established. It spans 103 years, in the period 1453–1555 AD. The last growth rings preserved in five samples enabled to determine the time of cutting down the fir trees, from which they came, to the years 1553–1555 AD (Fig. 25). The buildings from the Old Town in Rybnik were built in the middle of the 1550s.

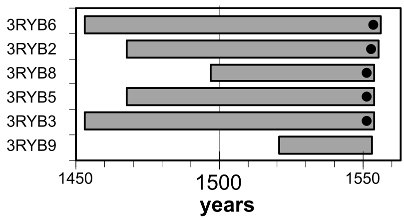


Fig. 25. Dendrochronological dating of growth sequences sampled from archaeological excavations in the Market Square in Rybnik. The last growth rings marked with dots

### Wodzisław Śl., Old Town

The archaeological excavations led in the Old Town in Wodzisław Śląski in 2002 (first stage) and in 2006 (second stage) provided fragments of wood which were subjected to the analyses. They came from structural elements of a wooden road and buildings at the Powstańców street, Konstancji street, and the Municipal Park. Amongst over 100 samples analysed, 87 represented fir wood, whereas the remaining wood was of pine, spruce, oak, elm, and poplar. The fir individual sequences contained various numbers of growth rings, from 22 to 82. On the basis of the best correlating samples, three average curves for this site were constructed, which represented different time intervals. Two curves were dated to the seventeenth century; the first one to the middle of the seventeenth century (1579–1658 AD), and the other to the end of the century (1637–1698 AD). The third and youngest curve was dated to the second decade of the nineteenth century (1732–1816 AD). The last growth rings were retained only in the youngest, nineteenth-century sequences (Fig. 26). Such distribution of the dating results suggests consecutive phases of introduction of wood at the reconstruction, repairs, or building new wooden structures.

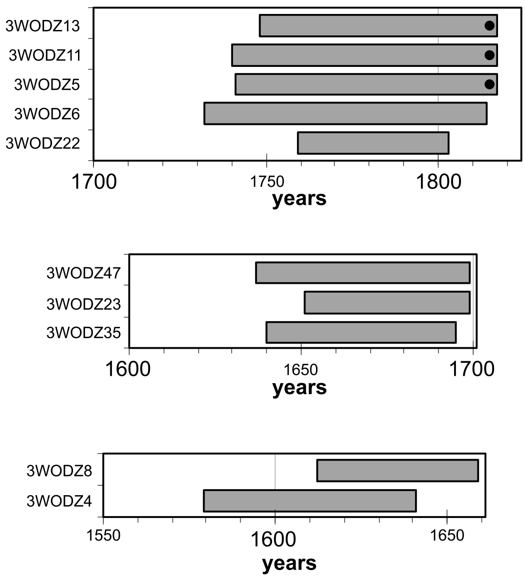


Fig. 26. Correlation diagrams of growth sequences sampled from archaeological excavations in the Old Town in Wodzisław Śl. The last growth rings marked with dots

## Oświęcim

A wooden element, lifted at the archaeological excavations led in Oświęcim, was subjected to the dendrochronological analysis. The wood represented the silver fir. The sequence consisted of 98 growth rings, but, unfortunately, it was incomplete; the last, youngest ring was missing. Absolute dating showed that the studied wood fragment came from the fir tree cut down at the beginning of the fourteenth century (1212–1309 AD).

## Grabie, church

The Church of the Assumption of Our Lady Mary in Grabie (Wieliczka county) was built in the 1740s (1742–1747). It is a little, wooden church, single-nave, of the framework structure (Faryna-Paszkiewicz *et al.* 2001). The nave is completed with a chancel, of the same height and width as the respective dimensions of the nave. The church, devoid of any tower, has only a little bell on the roof. A belfry stands by the church (Brykowski and Kornecki 1984). From the elements of the roof structure of the church, 18 samples of wood were collected: 14 of pine and four of fir. The fir sequences contained from 66 to 174 growth rings, unfortunately, the last ring was not preserved in any of them. On the basis of three individual curves, the object chronology was constructed, dated to the years 1555–1736 AD (Fig. 27). Since the youngest rings were not preserved in the examined elements of the roof structure, having added a number of missing rings, it is possible to state that the roof structure dates back to the time of the construction of the church.


Fig. 27. Dendrochronological dating of growth sequences sampled from the church in Grabie. The last growth rings marked with dots

### Wawrzeńczyce, church

The historic church of St. Mary Magdalene in Wawrzeńczyce (Kraków county) was built in place of an older church at the turn of the seventeenth and eighteenth centuries. It is a single-nave church with a baroque chapel (Faryna-Paszkiewicz *et al.* 2001). It was several times destroyed by fires and warfare, and every time rebuilt. At present, only in part it does have Gothic character. From the roof structure 13 samples were taken in the form of cores; twelve of them represented fir wood, and one – oakwood. In the Małopolska standard only one, 54-year-long sample was used, dated to 1565–1618 AD.

### Igołomia, palace

The palace in Igołomia (Kraków county) was built about 1800 (Faryna-Paszkiewicz *et al.* 2001). At present, it is used by the Institute of Archaeology and Ethnology of the Polish Academy of Sciences in Kraków. The palace was built on a plan of a rectangle, with a portico leaned on four Ionic columns. The palace is simple, without any overdone decorations. In 2005, eight samples in the form of cores were collected from the elements of the roof structure of the palace. They represented the wood of larch and fir. Fir sequences contained from 26 to 93 growth rings, in two of them the last rings were retained. Only one, the longest sequence with the last ring was successfully dated to 1781–1873 AD. This date points out the year of cutting down the fir tree, from which the construction element was made.

### Wiślica, church

The church, constructed in the third quarter of the fourteenth century, was described above, at presentation of the pine chronology. The fir wood was represented by four samples. In the case of the fir wood, the 138-year object chronology was produced, covering the years 1218–1355 AD. Since the individual sequences are not complete and they do not contain the last rings, one should add several increments. The dates obtained for the fir wood indicate that it came from fir trees cut down during the construction of the collegiate church, i.e. the third quarter of the fourteenth century.

## Chudów, castle

This object was described above, at the description of the pine material. Six samples of fir wood, handed over for the analyses, came from the construction elements of the castle. These were wooden cribs coming from the tower, the second, third and fifth storeys, and beams coming from the latrine. The sequences analysed were short; they contained from 36 to 61 growth rings, in none of them, unfortunately, the last ring was preserved. Based on three sequences, mutually best correlating, the object chronology was established, dated to the years 1451–1537 AD (Fig. 28). Somewhat older dates (1511 and 1514 AD) were obtained for cribs from the second and third storey of the tower, which may point the time of its construction for the 1520s–1530s. The youngest date (1537 AD) is related to the elements of the latrine, which could have been built later, in the 1540s or at the beginning of the 1550s. The wood examined most probably dates back to the time of the construction of the Chudów castle.

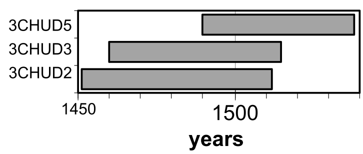


Fig. 28. Dendrochronological dating of growth sequences sampled from the castle in Chudów

## Kraków, building in 17 Kanonicza street

In December 1999, during renovation of the historic building, 48 fir samples in the form of slices were taken for analyses. Based on them, two object chronologies were compiled. The first one, dated to the years 1364–1528 AD, was produced from 20 best correlating individual sequences. They were of various lengths, contained from 37 to 133 growth rings, and in two of them the last growth rings were preserved (Fig. 29). The second, younger chronology was dated to the years 1705–1864 AD. It was composed of seven individual sequences, which contained from 83 to 150 growths, and six of them retained the youngest rings, beneath the bark (Fig. 30). Thanks to that, it was possible to determine the exact date of cutting down the fir trees, from which the wooden elements had been made. Two phases of introducing wood into the building could be distinguished; the older phase in 1838 and the younger one in 1863–4 AD. Based on that, it is possible to state that the nineteenth-century renovation and/or repairs took place in this building at the end of the 1830s and in the mid-1860s.

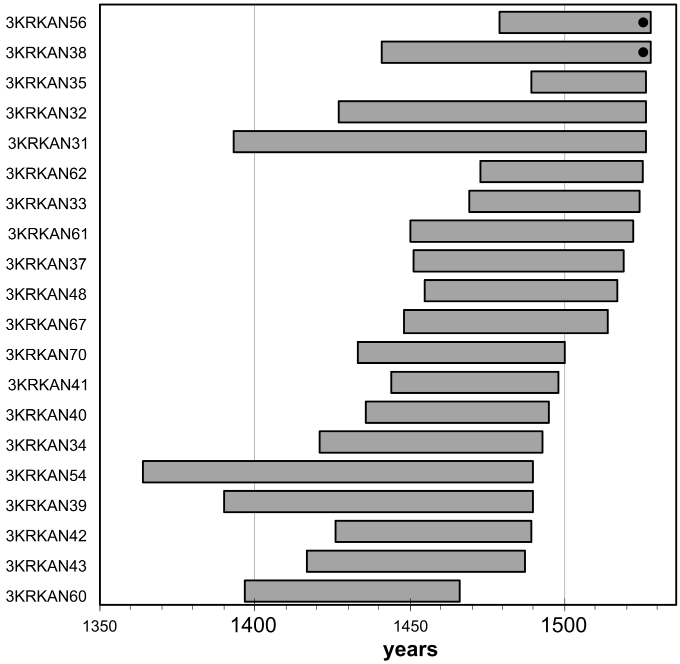


Fig. 29. Correlation diagram of growth sequences sampled from the historic building in 17 Kanonicza street in Kraków. The last growth rings marked with dots

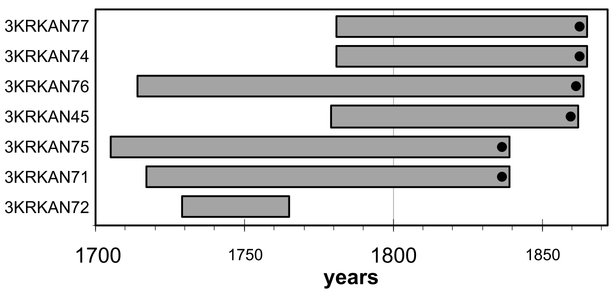


Fig. 30. Dendrochronological dating of growth sequences sampled from the historic building in 17 Kanonicza street in Kraków. The last growth rings marked with dots

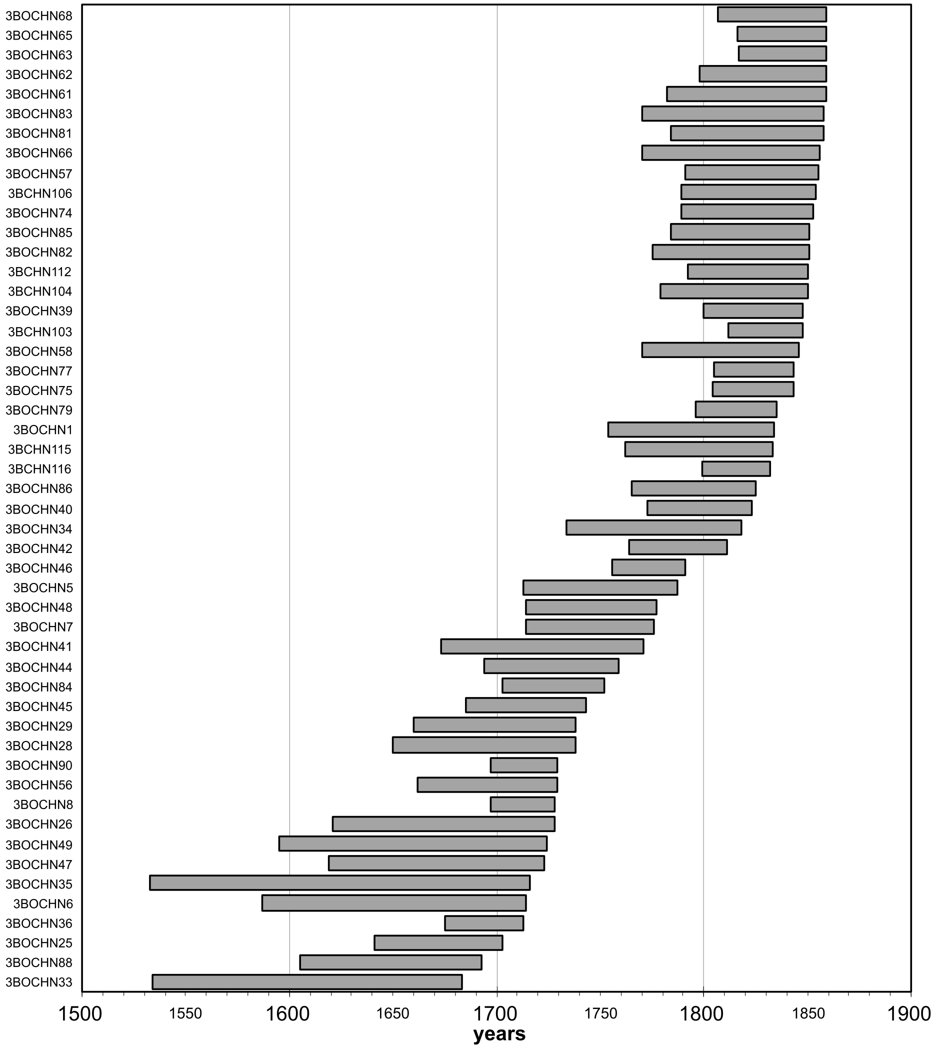


Fig. 31. Correlation diagram of growth sequences sampled from the Bochnia Salt Mine

## Bochnia, salt mine

The Małopolska regional chronology includes 50 samples from the Bochnia Salt Mine. They represent above all the nineteenth (61%) and eighteenth (32%) centuries. The older periods of time, the sixteenth and seventeenth centuries, are represented only by 5% of the samples included into the standard, and the twentieth century – by one sample (2%) only (Fig. 31). Taking into account the number of samples taken and dated, wherever it was possible the object chronologies were produced for some mining chambers, e.g. the Stanetti Chambers (Fig. 32). In numerous cases the dendrochronological dating is in agreement with the historic source data, e.g. the Stanetti Chambers, which were exploited from the beginning of the 1820s till the mid-twentieth century, contain casings originating from that period of time – 1824–1858 AD. The horse gear Ważyn of Saxon origin was dated to 1673, 1702 AD, whereas the filling in the Rabsztyn Basket, according to the source data originating from the 1730s, was absolutely dated to 1721, 1728, 1738, 1740 AD.

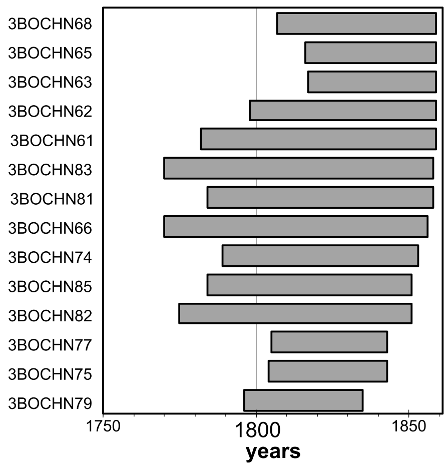


Fig. 32. Dendrochronological dating of growth sequences sampled from the mining casings in the Stanetti chamber in the Bochnia Salt Mine

## Magurski National Park

The Magurski National Park is situated in the Podkarpackie voivodeship. It is the most forested park in Poland (95.7%), the forest surface is 18,571 ha. The predominating tree species are beech, pine, and fir (Stępień-Sałek 2004). In the forest divisions 59c, 56c ,and 52f 61 samples were taken for dendroecological studies (Lech 2006). On the basis of these samples, which finally were not used in the dendroecological research (because of lack of reductions of the increment widths), the site chronology was constructed. The 130-year pattern covers the period 1875–2004 AD.

### Ojców National Park

The Ojców National Park is situated about 20 km NW from Kraków. The forest areas cover about 80% of the surface of the park. The dominating tree species are Scots pine (27% of the surface of the park) and silver fir (24% of the surface of the park) (Ząbecki and Wierus 1993). The samples for the analysis were taken from fir trees growing in the eastern part of the Prądnik Valley, at two sites. The first site was situated in the hill Okopy, and the second site – near the gorge Wilczy Dół, about 1.5 km from the hill Okopy. Altogether 40 samples were collected. Based on 13 best correlating samples the 115-year site chronology was established. It covers the years 1886–2000 AD.

In the fir chronology newly constructed, like in the case of the pine chronology, a part of the material was used, which was included into the composition of the South-Polish fir standard, already published by the author (Szychowska-Krąpiec 2000). Below they are only briefly mentioned.

### Bytom, Market Square

On the basis of wood coming from the first stage of the research (1998) the local chronology was established (1156–1294 AD). It was supplemented with individual patterns coming from samples provided in the second stage of the research in 1999. Taking into account 15 best correlating individual sequences, the new average pattern was compiled, covering the years 1156–1294 AD. In eight individual sequences the last growth rings, beneath the bark, were preserved. They date the time of cutting down the fir trees of which wood the stalls and the surface of the Market were made with one-year accuracy to 1294 AD.

### Sandpit at Hutki (Olkusz county)

In 1998, while carrying the excavation work on in the sandpit, fragments of wood were brought out in the form of beams and boards. On the basis of 11 best correlating individual sequences, containing from 36 to 109 growths, the local chronology was constructed, covering the years 1169–1328 AD. In five samples the last growth ring was preserved, dating the structural elements for the years 1320 and 1328 AD.

### Bielsko-Biała

At the excavation work in Bielsko-Biała two fir beams were taken out. The average curve produced from them is 67-year-long and covers the period 1477–1543 AD.

### Jaszczurowa (Świnna Poręba common)

The research material was fir wood lifted at the excavation work made at the site 22. At construction of the present standard, three individual sequences were used. They form the 37-year site chronology, spanning the years 1495–1531 AD.

R o ż n ó w

The wood analysed came from archaeological excavations and represented exclusively the silver fir (six samples). Dendrochronological analysis of three samples indicated that they originated from two periods of time; two older samples from the seventeenth century (1659, 1660), and the younger one from the nineteenth century (1810 AD). The older individual patterns were short, contained from 39 and 47 growth rings, unfortunately in none of them the last growth was preserved. The younger sequence was considerably longer (91 increments) and retained a complete sequence with the earlywood developed, which proves that the fir tree from which the element examined was made was cut down during the vegetation season (July/August).

W o l i c a

At the exploitation in the Wolica gravel pit, situated on the left bank of the Vistula River, about 20 km from Kraków, a wooden construction was encountered. The object chronology compiled is 69-year long and covers the period 1702–1770 AD. At present, ten best correlating sequences were used.

P a c z ó ł t o w i c e

Church in Paczółtowice (Kraków county), of Hitting Our Lady Mary. The object chronology produced on the basis of wood from the church was dated to the years 1385–1508 AD. At present, seven samples were used for construction of the Małopolska standard.

W i e l i c z k a, s a l t m i n e

The dendrochronological research carried out resulted in construction of over 600-year chronology, covering the years 1267–1903 AD, based on 178 fir samples. It is a part of the South-Polish standard. In the Małopolska standard newly created, 163 samples were used, coming from trees growing from the fourteenth till the twentieth century. All samples came from the first and oldest level of the mine, mainly from wooden casings, so-called casts.

B a r n o w i e c

Barnowiec reserve, of the surface 21.61 ha, established in 1924, is situated in the Jaworzyna Krynicka Range in the Poprad Landscape Park. On the basis of 24 individual sequences, the 226-year object chronology was produced, covering the period 1771–1996 AD.

K ą ś n a

Kąśna, Gromnik forest district. The research site was located in the division 101s, about 2 km to the west from Ciężkowice. 23 samples were taken from fir trees constituting the seed forest stand. On the basis of 18 individual sequences, the average curve for this site was compiled, spanning the years 1872–1998 AD.

Kraków

Building in Św. Wawrzyńca street. During renovation of the roof structure, 14 samples of fir wood were taken. On the basis of eight individual sequences, mutually best correlating, the average 68-year curve was constructed, covering the period 1840–1907 AD.

Building in Św. Krzyża street. Seven slices representing the fir wood came from wooden elements of the roof ceiling. On the basis of five individual sequences, the object chronology was constructed, dated to the years 1738–1801 AD.

Building in 16 Kanonicza street. During renovation of inhabited rooms in two stages, samples for analyses were taken from boards and beams of the ceiling. In the first stage 14 samples were collected, on the basis of which the object chronology was compiled, dated to the years 1183–1455 AD. In the second stage, 15 ceiling boards were sampled. On the basis of 16 individual sequences, mutually best correlating, the 296-year object chronology was constructed, spanning the period 1183–1478 AD.

Building in Grodzka street/Central Market Square. On the basis of fir wood gathered at the renovation of a building, two object chronologies were constructed. The older chronology was dated to 1724–1850 AD, whereas the 110-year younger one spans the years 1847–1956 AD.

Building in W. Tetmajera street. At the renovation of the building called 'Tetmajerówka', 40 samples in the form of circular slices were taken for analysis. Two chronologies produced were dated to the nineteenth century; the first one to 1702-1872 AD and the second chronology to 1819–1893 AD.

Building of the UJ (Jagiellonian University) Museum – Collegium Maius. The sampling object was a wooden ceiling in one of the rooms. Three samples were taken in the form of cores. The chronology constructed covers the period 1350–1489 AD.

Building of the Psychiatric Hospital in Kobierzyn. During the renovation of the building, 20 fir samples were taken in the form of circular slices. On the basis of the individual sequences mutually best correlating the average curve of the object was constructed. It counts 90 years and spans the years 1822–1911 AD (Szychowska-Krąpiec 2000).

Characteristics of the fir chronology

The Małopolska standard is the second Polish, ca. 900-year-long, regional chronology for the fir wood. It consists of 560 samples, on the basis of which 35 object and/or site chronologies were composed (Fig. 33). They were checked with the COFECHA program from the package of programs DPL. Using the bridge dating, going from the youngest chronologies established on the basis of living trees to the oldest ones, built on historical wood appearing in wooden objects, salt mines, and archaeological excavations, the standard was produced, covering the years 1109–2004 AD. Seventeen chronologies were based on wood coming from architectural objects, twelve were produced from wood explored from archaeological excavations, four others represented living trees, and two chronologies were compiled on the basis of wood from the salt mines in Wieliczka and Bochnia. As far as site chronologies are concerned, the average pattern from the Wieliczka Salt Mine merits attention. It consists of 162 wood samples and covers the period 1267–1903 AD. Most of the samples building the regional standard came from the mines (41.4%), the least number – from living trees (9.3%), whereas the figures of samples coming from architectural objects (22.7%) and archaeological excavations (26.6%) are comparable.

Table 2

Characteristics of the local chronologies forming the Małopolska fir standard

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Kraków, Central Market Square, archaeological excavations, wooden structures | 3KRRY_1 | 1109–1374 | 266 | 111 | 0.807 37.245 | 1.22 | 0.477 | 0.852 | 0.167 |
| 2 | Bytom, Market Square, archaeological excavations, wooden structures | 3BYT_1 | 1156–1294 | 139 | 15 | 0.715 16.271 | 1.49 | 0.539 | 0.785 | 0.178 |
| 3 | Hutki, sandpit, wooden structures | 3HUT_1 | 1169–1328 | 160 | 11 | 0.697 15.609 | 1.48 | 0.476 | 0.772 | 0.175 |
| 4 | Kraków, 16 Kanonicza street, inhabited building, ceiling beams and boards | 3KAN_1 | 1183–1478 | 296 | 16 | 0.617 15.948 | 1.24 | 0.607 | 0.895 | 0.184 |
| 5 | Oświęcim | 3OSW_1 | 1212–1309 | 98 | 1 | 0.572 7.096 | 1.17 | 0.443 | 0.734 | 0.204 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | Wiślica, church, elements of roof structure | 3WIL_1 | 1218–1355 | 138 | 2 | 0.437 8.478 | 1.86 | 0.698 | 0.804 | 0.177 |
| 7 | Wieliczka Salt Mine, wooden casings of mining excavations | 3WIE_1 | 1267–1903 | 637 | 162 | 0.748 39.605 | 1.50 | 0.544 | 0.879 | 0.140 |
| 8 | Kraków, building UJ, Collegium Maius, ceiling beams | 3KUJ_1 | 1350–1489 | 140 | 3 | 0.588 9.057 | 1.31 | 0.693 | 0.849 | 0.236 |
| 9 | Kraków, 17 Kanonicza street, inhabited building, ceiling beams and boards | 3KAN_2 | 1364–1528 | 165 | 23 | 0.658 13.156 | 1.63 | 0.765 | 0.896 | 0.173 |
| 10 | Paczółtowice, church, elements of wall structure | 3PAC_1 | 1385–1508 | 124 | 7 | 0.560 9.518 | 1.94 | 1.114 | 0.930 | 0.190 |
| 11 | Chudów, castle, elements of roof structure and latrine | 3CHU_1 | 1451–1537 | 87 | 3 | 0.723 12.947 | 2.35 | 0.828 | 0.849 | 0.154 |
| 12 | Rybnik, Old Town, archaeological excavations, wooden structures | 3RYB_1 | 1453–1555 | 103 | 6 | 0.600 10.402 | 1.22 | 0.387 | 0.834 | 0.154 |
| 13 | Bielsko-Biała, archaeological excavations, wooden structures | 3BBA_1 | 1477–1543 | 67 | 2 | 0.522 7.262 | 2.17 | 0.465 | 0.536 | 0.162 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 14 | Jaszczurowa, archaeological excavations site 22, wooden structures | 3JAS_1 | 1495–1531 | 37 | 3 | 0.414 8.960 | 2.17 | 0.576 | 0.637 | 0.182 |
| 15 | Bochnia Salt Mine, wooden casings of mining excavations | 3BOC_1 | 1533–1858 | 326 | 50 | 0.738 22.446 | 1.58 | 0.705 | 0.905 | 0.164 |
| 16 | Grabie, church, elements of roof structure | 3GRA_1 | 1555–1736 | 182 | 3 | 0448 9.426 | 1.07 | 0.334 | 0.744 | 0.175 |
| 17 | Wawrzeńczyce, church, elements of roof structure | 3WAWW3 | 1565–1618 | 54 | 1 | 0.656 5.251 | 1.95 | 1.016 | 0.824 | 0.250 |
| 18 | Wodzisław Śl., Old Town, archaeological excavations, wooden structures | 3WOD_1 | 1579–1658 | 80 | 2 | 0.556 5.617 | 1.86 | 0.787 | 0.802 | 0.212 |
| 19 | Rożnów, archaeological excavations, wooden structures | 3ROZ_1 | 1613–1660 | 48 | 2 | 0.747 9.610 | 2.44 | 0.668 | 0.364 | 0.234 |
| 20 | Wodzisław Śl., Old Town, archaeological excavations, wooden structures | 3WOD_2 | 1637–1698 | 62 | 3 | 0401 5.330 | 2.99 | 1.259 | 0.895 | 0.158 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | Kraków, Grodzka street/Market Square, inhabited building, elements of building structure | 3KRG_1 | 1686–1858 | 173 | 9 | 0.594 10.666 | 1.82 | 0.912 | 0.895 | 0.182 |
| 22 | Wolica, gravel pit, wooden structure | 3WOL_1 | 1702–1770 | 69 | 10 | 0.666 5.697 | 3.31 | 0.841 | 0.725 | 0.151 |
| 23 | Kraków, Tetmajerówka, elements of building structure | 3KTT_1 | 1702–1872 | 171 | 10 | 0.672 11.008 | 2.17 | 0.607 | 0.714 | 0.183 |
| 24 | Kraków, 17 Kanonicza street, inhabited building, ceiling beams and boards | 3KAN_3 | 1705–1864 | 160 | 7 | 0.787 15.526 | 2.35 | 0.679 | 0.703 | 0.184 |
| 25 | Wodzisław Śl., Old Town, archaeological excavations, wooden structures | 3WOD_3 | 1732–1816 | 85 | 5 | 0.761 11.485 | 1.73 | 0.822 | 0.825 | 0.215 |
| 26 | Kraków, Św. Krzyża street, inhabited building, ceiling elements | 3KSK_1 | 1738–1801 | 64 | 5 | 0.747 7.898 | 1.95 | 0.0.618 | 0.780 | 0.170 |
| 27 | Barnowiec, reserve, living trees | 3BAR_1 | 1771–1997 | 227 | 22 | 0.538 13.397 | 1.72 | 0.602 | 0.848 | 0.141 |
| 28 | Kraków, Św. Wawrzyńca street, inhabited building, elements of roof structure | 3KWA_1 | 1774–1907 | 134 | 8 | 0.620 9.338 | 1.57 | 0.570 | 0.771 | 0.208 |

| No | Description | Laboratory code | Sequence dating | Sequence length | No of samples in chronology | Correlation with standard [*r*], [*t*] | Average tree-ring width [mm] | Standard deviation | Autocorrelation | Mean sensitivity |
|---|---|---|---|---|---|---|---|---|---|---|
| 29 | Igołomia, palace, elemens of roof structure | 3IGL_1 | 1781–1873 | 93 | 1 | 0.465 6.948 | 1.00 | 0.989 | 0.07 | 0.279 |
| 30 | Kraków, Tetmajerówka, elements of building structure | 3KTT_2 | 1819–1893 | 75 | 3 | 0.559 7.734 | 2.17 | 0.607 | 0.714 | 0.183 |
| 31 | Kraków, Kobierzyn, building no 7, elements of roof structure | 3KKB_1 | 1822–1911 | 90 | 9 | 0.722 9.892 | 2.31 | 0.812 | 0.763 | 0.184 |
| 32 | Kraków, Grodzka street/Market Square, inhabited building, elements of building structure | 3KRG_2 | 1847–1956 | 110 | 6 | 0.745 13.728 | 1.86 | 0.516 | 0.634 | 0.182 |
| 33 | Kąśna, Gromnik forest district, living trees | 3KAS_1 | 1872–1998 | 127 | 15 | 0.787 18.624 | 2.35 | 0.679 | 0.703 | 0.184 |
| 34 | Magurski National Park, living trees | 3MGP_1 | 1875–2004 | 130 | 11 | 0.740 13.788 | 2.22 | 0.517 | 0.462 | 0.192 |
| 35 | Ojców National Park, living trees | 3OJC_1 | 1886–2000 | 115 | 13 | 0.731 10.891 | 2.19 | 0.712 | 0.645 | 0.189 |

Table 2 presents characteristics of individual object chronologies, i.e. absolute dating, length of the sequence, number of samples included in every chronology, correlation with the standard (value *t* and correlation coefficient r), medium width of tree rings, standard deviation, autocorrelation, and mean sensitivity. The average tree-ring width in the fir chronology amounts to 1.66 mm and is comparable with the average tree-ring width in the pine chronology (1.8 mm). The average standard deviation (0.625) is lower than in the case of the pine chronology. The values of average autocorrelation (0.819) and average sensitivity (0.172) are very similar to the values obtained for the pine chronology. They prove that the time series constructed – the fir chronology – is not random, but the sequence of data correlated correctly. The average sensitivity of the trees to the environmental stresses is relatively moderate, similar to the average sensitivity of the trees in the Małopolska pine chronology.

The replication of the fir chronology is very good; except 70 initial years it amounts to over 20 samples in every year (Fig. 34). From the middle of the fifteenth century all the way to the present the number of the samples does not fall below 50. Particular attention should be paid to the thirteenth and the first half of the fourteenth century, when the sample figures were well over 50 and in certain time even reached the values of 90–100 (the years 1250–1290). Such a high replication in the thirteenth and the first half of the fourteenth century is connected with rich archaeological material from the Kraków Central Market Square. In the years 1350–1430, the fall of the sample figures in the chronology to about 20–30 may be observed, which is related to the deficiency of wood samples from that period of time. From 1430, the replication increases to 30 samples and more and then, in any year, it does not drop below 40, except the last years in the 21$^{st}$ century.

As at the pine standard, the class of the age of the trees building the fir chronology was evaluated. The assessment was based on 20-year-long age classes. The youngest class is formed by the samples from trees of the age below 30 years, and the oldest one – 250–269 years. The youngest class was distinguished at the fir on the account of its strong dendrochronological signal, caused by a low species changeability of this taxon.

In the chronology discussed, the samples coming from young trees, of the age classes between 30 and 90 years, are dominating (about 75%), which is different than in the pine chronology, in which samples from a little bit older trees, 70–129-year, prevail. Such a high percentage participation of samples coming from young fir trees is positive, since individual sequences are not disturbed and/or burdened with the senile trend, which facilitates their correlation, dating and interpretation. The lowest participation in the newly constructed chronology is made by samples coming from the youngest trees (below 29 years) and the oldest ones, from 110 to 269 years (Fig 35).

It should be remembered that in the case of historical wood from historical objects, archaeological excavations, as well as mines the assessment of the age class cannot be strictly accurate, because of sometimes incomplete individual sequences. Such an assessment, however, despite everything, demonstrates at least approximate age distribution of the trees, from which the samples were taken for the analyses.

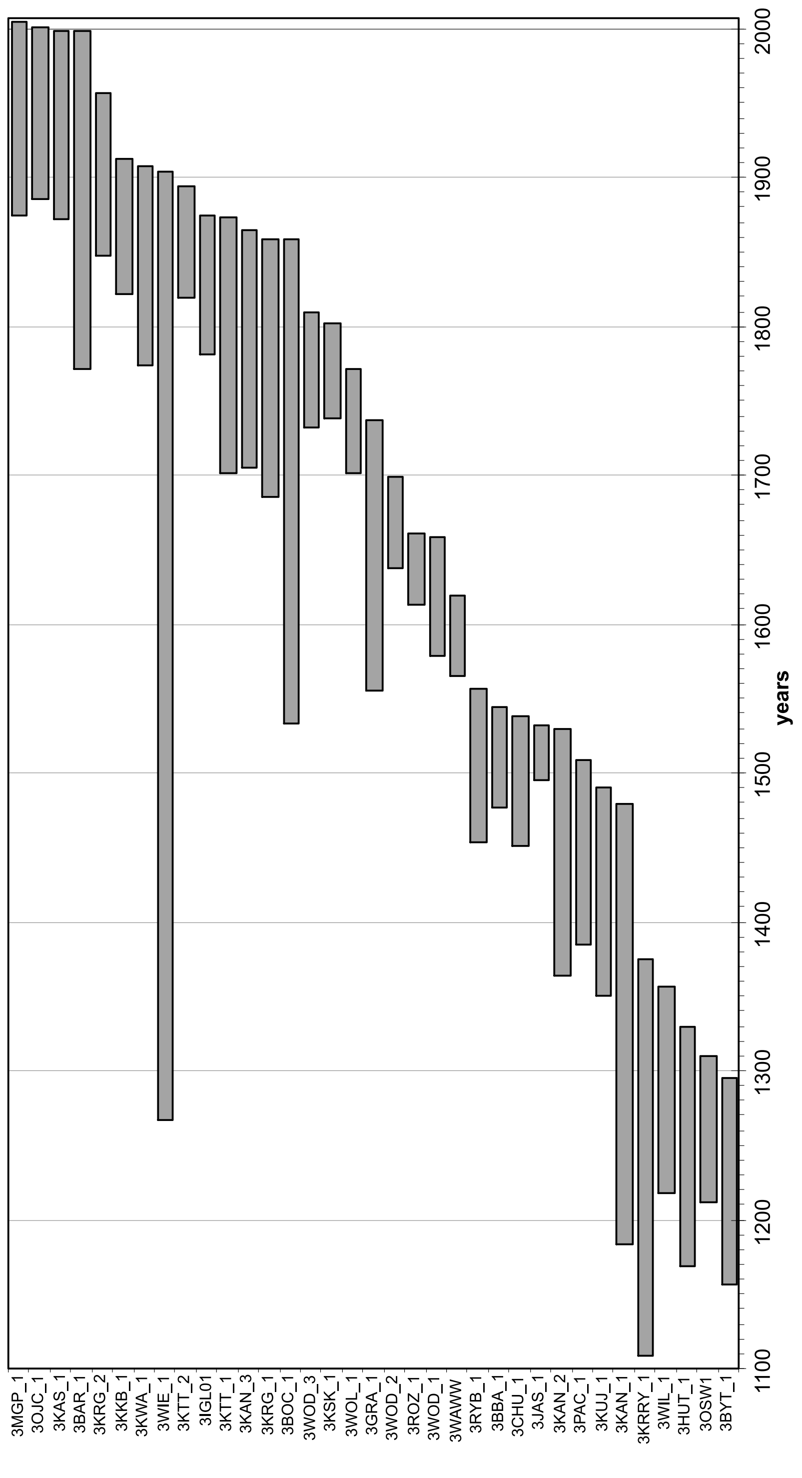


Fig. 33. Local and object chronologies forming the master fir chronology for the Małopolska region covering the years 1109-2004 AD

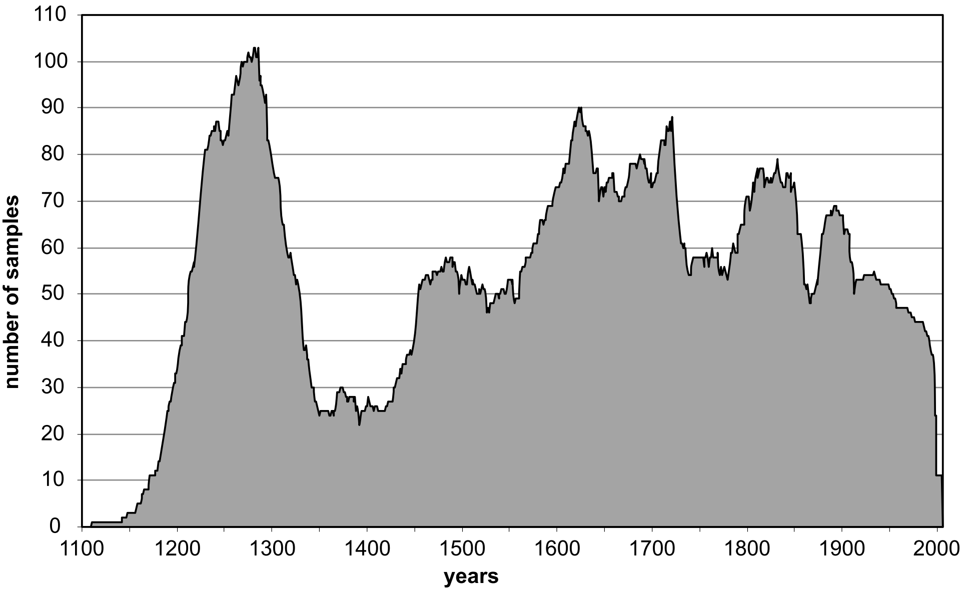


Fig. 34. Replication of the tree-ring sequences in the master fir chronology for the Małopolska region in the period 1109–2004 AD

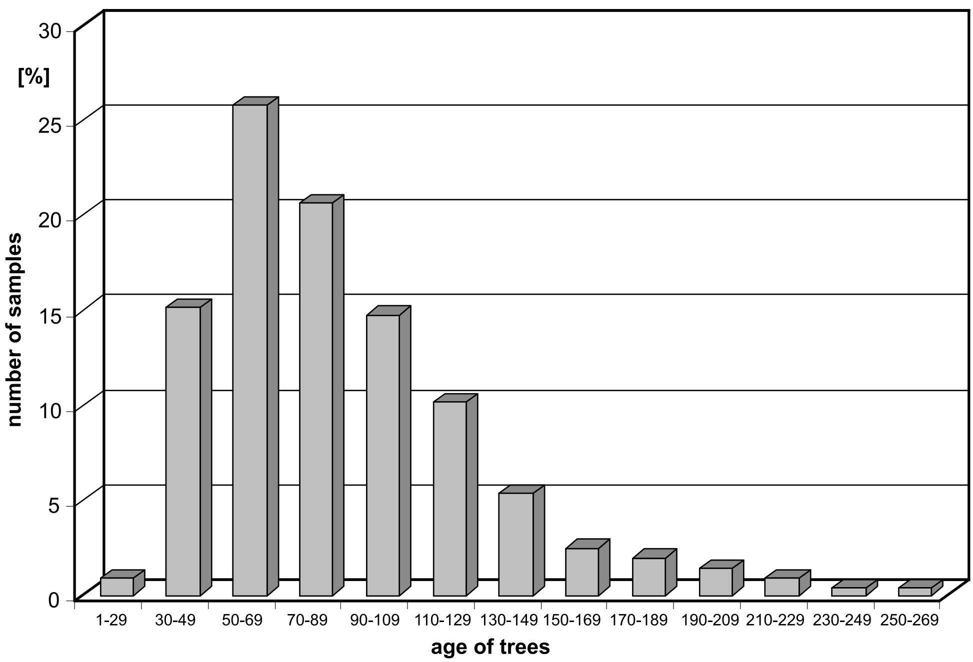


Fig. 35. Percentage parts of the 20-year age ranges of trees forming the Małopolska fir chronology

# TELECONNECTION AND HETEROCONNECTION OF REGIONAL CHRONOLOGIES

## Teleconnection

Teleconnection is the similarity of the chronologies of annual growth sequences of trees representing the same tree species, but growing in distant areas. This term was introduced by a Swedish geologist G. De Geer, who investigated geographical extent of varved-clay sequences from different sites in Scandinavia and made their mutual comparisons. He considered that the variations in thickness observed in the varved clays are caused, alike as in the case of the tree rings, by cosmic factors of worldwide extent. Having adopted such an assumption, he attempted to date the varved clays from the Southern Hemisphere against the Swedish curves, which ended in failure. In the 1950s, Ebba de Geer tried to prove the resemblance between incremental curves of Swedish trees and American sequoias, however, without satisfactory results. An attempt of teleconnection of the incremental sequences of sequoias with dendrochronological sequences of the pine and oak wood excavated in the settlement Biskupin ended negatively as well. At the same time, teleconnection was attempted for the spruce wood from Alaska, Labrador and Northern Europe; unfortunately, this also ended in failure. The investigations carried out by Müller-Stoll (1951) proved that the similarity between the incremental sequences of the compared trees depended on the tree species as well as the distance between the analysed sites. In the case of the same taxon and relatively little distance the similarity is high. She also stated that the similarity is more dependent on the tree species, of which the sequences are being compared, than the distance between the areas in question. According to this author, there is not any resemblance between the dendrochronological sequences of trees from Central Europe and Scandinavia, and, moreover, between Europe and North America. Huber (1943) presented similar views, having been in favour of teleconnection in the areas of similar climatic conditions, for instance in Central Europe.

At the end of the 1980s, the transcontinental teleconnection of the tree-ring standards with the varved-clay profiles was attempted once more, but, as earlier, also ended in failure (Shove 1987). Since that time the teleconnection was applied only to comparison of the dendrochronological standards or to correlation of the varved-clay profiles. The investigations of, among others, Hollstein (1980) and Schweingruber (1985) confirmed the opinion of Müller-Stoll that the resemblance between the dendrochronological standards compared is decreasing with the distance. According to these authors, however, the deciding meaning in the teleconnection has not only the distance, but also the growth conditions of the trees (habitat), which directly affect the degree of the resemblance of the chronologies compared, and the growth region, cohesive as to the geographical and climatic conditions.

In Poland, the first attempts of teleconnection were carried out by Ermich (1960). This author compared the dendrochronological sequences of the oaks growing in the forest district Miechów with the oak sequences of the same species from Bavaria. These attempts generally ended in failure, low similarity was noted only for the oaks from Miechów and the oaks from Spessart. Lack of similarity between the annual growths of oaks could be related to the fact that some of the specimens analysed did not come from their natural habitats, and the Miechów sequence had low replication; it consisted of only seven individual sequences, which could be a cause of too faint dendrochronological signal. It should be noted that an essential element at obtaining high teleconnection of the standards compared is their replication, i.e. covering of every individual year by a number of samples. According to Schweingruber (1996), the average of 15–20 trees should be sufficient, although it may happen, especially at disturbed and/or non-typical sequences, that even the number of 30 would be insufficient. On the other hand, however, it sometimes happens that even a figure below ten samples would be satisfactory.

A good example of this type of procedure is dating the chronology of sub-fossil oaks from the vicinity of Racibórz, constructed by Goslar (1987). It was dated to the period 412–735 AD against the oak chronology constructed by Becker (1982) for Southern Germany, Austria, and Switzerland.

The teleconnection is, however, always used for testing the correctness of construction of the new standards. They are most often compared with the regional chronologies from the neighbouring areas, to which the distance is not too high (several hundred kilometres), and the climatic conditions are similar. For the newly constructed Małopolska chronologies, the teleconnection was carried out with corresponding standards for the areas situated in the same climatic zone (Central and Southern Germany, Austria, Czech Republic, Northern Poland, and the island of Gotland). These areas are situated in the warm moderate zone of the transitory climate. This type of the climate is controlled by the influence of two permanent barometric centres: the Azorean High and the Icelandic Low, which generally bring about the inflow of humid air from above the Atlantic. This, in turn, results in quite mild winters, with the average temperature of January from –10°C to 0°C. The distribution pattern of the January temperatures is longitudinal, and the above temperature range stretches from Germany till the surroundings of Kiev. The summers in this climatic zone are not too hot, with the average temperatures of July from 10°C to 20°C, but, contrary to the January temperatures, they display the latitudinal arrangement, spreading from France till the Ural Mts. The second important climatic factor affecting the formation and width of the tree rings at the pine and fir is the rainfall, in this climatic zone being from 25 to 50 mm in January and from 50 to 100 mm in July. Due to moderate temperatures of winter and summer months as well as moderate averages of the total monthly precipitation, the areas in which the fir and pine trees grew are climatically cohesive and they allow for developing the incremental patterns so similar, that carrying out the teleconnection is possible.

Therefore, for two newly constructed standard chronologies the teleconnection was made with the accessible regional chronologies from the areas mentioned above.


Fig. 36. Teleconnection of the Małopolska fir chronology with the European fir standards: 1 – Małopolska fir chronology, 2 – Central-German chronology, 3 – South-German chronology, 4 – East-Austrian chronology, 5 – Czech chronology

The fir sequence was compared with five accessible regional standards, between ca. 700 and 1000 years in length, from the adjacent areas:

– Central Germany (Saxony and Thuringia (994–1921 AD) (Heussner 1996),
– Southern Germany (820–1985) (Becker and Giertz-Siebenlist 1970),
– Eastern Austria (977–1997 AD) (Liebert et al. 1998),
– Czech Republic (1131–1997) (Kyncl and Kyncl 1996),
– Southern Poland (1106–998 AD) (Szychowska-Krąpiec 2000).

The Małopolska fir chronology demonstrates the highest similarity to the Austrian standard ($t$ = 20.079) and the German one for Saxony and Thuringia ($t$ = 19.928), and somewhat lower, however, similarity to the incremental pattern for the Czech standard ($t$ = 17.348). The similarity with the South-German chronology, expressed with the value t, amounts to 18.568. Generally, the values of the similarity of the Małopolska fir chronology with the standards from the neighbouring countries are rather close and reach high values of $t$ (Fig. 36). A little bit lower values of the teleconnection with the South-German and Czech chronologies are caused by a relatively high distance in the case of the South-German one, the highest of all the chronologies compared, about 1,000 km in a straight line, whereas the Czech sequence has relatively low replication (the number of individual sequences included in it amounts to only 156) (Kyncl and Kyncl 1998), which may somewhat decrease the value *t* at the teleconnection. Apart from that, the Czech chronology is the shortest one of the standards compared, it counts 767 years, whereas the other ones about 1000 years (Table 3). The highest similarity ($t = 44.834$), considerably higher than in the other cases, was obtained, as expected, for both Polish standards. This is caused by similar growth conditions of the trees building this sequence, short distance, as well as by the fact that some sequences are shared by both chronologies.

Table 3

Comparison of the newly created fir chronology with accessible regional fir standards from adjacent areas (teleconnection)

| Fir chronologies | Małopolska fir chronology | |
|---|---|---|
| | (*t*) | (*r*) |
| Southern Poland (1106–1998 AD) *Abies alba* | 44.834 | 0.833 |
| Central Germany (994–1921 AD) *Abies alba* | 19.928 | 0.574 |
| Southern Germany (820–1985 AD) *Abies alba* | 18.568 | 0.533 |
| Eastern Austria (977–1997 AD) *Abies alba* | 20.079 | 0.560 |
| Czech Republic (1131–1997 AD) *Abies alba* | 17.348 | 0.509 |

The teleconnection carried out for the fir is characterized with very high values, around $t = 20$. Such high values are characteristic only for the fir, on the account of its low individual variability and very strong dendrochronological signal. This is confirmed by the teleconnection values obtained for other tree species, e.g. oak, for which the maximal values of the teleconnection amount to 11.4–12.8 (teleconnection of the Wielkopolska chronology for oak with the chronologies for Central and Southern Germany) (Krąpiec 1998).

The teleconnection was also carried out for the newly created pine chronology. It was compared with five Polish chronologies (two 900-year-long and three 400-year-long) and two available chronologies for the neighbouring countries:

- North-Polish chronology (1106–1991 AD) (Zielski 1997),
- Kujawy-Pomerania chronology (1164–2000 AD) (Krąpiec et al. 2005),
- Warmian-Mazurian chronology (1518–2003 AD) (Szychowska-Krąpiec and Krąpiec 2006),
- Suwałki region chronology (1582–2004 AD) (Szychowska-Krąpiec and Krąpiec 2005),
- chronology for the island of Gotland (1124–1987 AD) (Bartholin 1987),
- Central-Germany chronology (Saxony and Thuringia) (924–1985 AD) (Heussner 1996).

The obtained values of the similarity are considerably lower than in the case of the fir standard. This results from the specific character of the pine, considered as a species difficult in dendrochronological analyses, on the account of its high individual variability and occurrence of multiple varieties (Fig. 37).


Fig. 37. Teleconnection of the Małopolska pine chronology with the regional pine chronologies: 1 – Małopolska pine chronology, 2 – Central-German chronology, 3 – North-Polish chronology, 4 – Kujawy-Pomerania chronology, 5 – Gotland chronology, 6 – Warmia-Mazury chronology, 7 – Suwałki region chronology

The highest similarity of the Małopolska chronology with the standards compared ($t > 10$) could be observed for two chronologies: Kujawy-Pomerania ($t = 12.137$) and Central Germany ($t = 10.789$). Both chronologies have high replication, which is essential in the case of pine, on the account of its high variability. Somewhat higher $t$-value, noted at the teleconnection with the Kujawy-Pomerania chronology, is probably connected with closer distance to Kujawy than to Saxony. On the other hand, the German chronology is the longest standard used in the teleconnection carried out and, in spite of higher distance, the $t$-value exceeded 10. Considerably lower similarity appeared at the teleconnection of the Małopolska standard with the second regional chronology for Northern Poland. This lower value may be explained by relatively low replication of the samples (below 10) in the time interval 1440–1650 AD in the North-Polish chronology. The teleconnection with the remaining, shorter chronologies for Northern Poland reaches similar *t*-values, between 6 and 8 (the highest for the Warmian-Mazurian chronology, $t = 8.568$). The comparison of the Małopolska standard with the incremental pattern from Gotland demonstrated the similarity value close to the North-Polish chronologies, $t = 6.544$. The obtained values of the similarity of the newly created chronology with the available regional chronologies confirm the correctness of the chronology construction and demonstrate its high potential as a dating tool (Table 4).

Table 4

Comparison of the newly created pine chronology with accessible regional pine standards from adjacent areas (teleconnection)

| Pine chronologies | Małopolska pine chronology | |
|---|---|---|
| | (*t*) | (*r*) |
| Northern Poland (1106–1991 AD) *Pinus sylvestris* | 6.687 | 0.220 |
| Kujawy-Pomerania (1164–2000 AD) *Pinus sylvestris* | 12.137 | 0.389 |
| Warmia-Mazury (1518–2003 AD) *Pinus sylvestris* | 8.568 | 0.364 |
| Suwałki region (1582–2004 AD) *Pinus sylvestris* | 6.652 | 0.310 |
| Gotland (1124–1987 AD) *Pinus sylvestris* | 6.544 | 0.218 |
| Central Germany (924–1985 AD) *Pinus sylvestris* | 10.789 | 0.339 |

## Heteroconnection

For some time, successfully applied dendrochronological practice consists in mutual comparison of the chronologies of various tree species, of which a purpose is the identification of the contemporary sequences. The procedure of establishing similarity between incremental sequences of different taxons is named the heteroconnection (Schweingruber 1996, Billamboz 2002). The heteroconnections are quite often carried out between four principal coniferous species, such as the Scots pine, silver fir, European larch, and common spruce. Among the deciduous taxons, high similarity of the annual growth sequences is displayed by the oak with the beech, elm, ash, and alder. Similar shapes of the annual growth sequences at different tree species depend, above all, on the climatic conditions, although not without meaning are such factors as: the tree age, the habitat, or the impact of the anthropopression. Similar reactions of different taxons of the trees to the climate factors, especially the extreme ones, are expressed with narrower or wider annual growth rings, which decide about similar shapes of the incremental patterns. The heteroconnection carried out for the Małopolska standards for the fir and pine demonstrated certain convergence between both species.

In the case of the Małopolska fir standard, the highest similarity was noted with the newly constructed Małopolska pine chronology (*t* = 9.811) and with the Kujawy-Pomerania standard (*t* = 9.832) (Fig. 38). In the case of the Małopolska fir and pine standards, high value of the heteroconnection is quite easy to explain, because the incremental sequences of both the firs and pines from Małopolska were shaped by the impact of the same climatic parameters. On the other hand, such a high value of the similarity between the Małopolska fir standard and the Kujawy-Pomerania pine chronology is hard for the explicit interpretation.


Fig. 38. Heteroconnection of the Małopolska fir chronology with the regional pine chronologies: 1 – Małopolska pine chronology, 2 – Central-German chronology, 3 – North-Polish chronology, 4 – Kujawy-Pomerania chronology, 5 – Gotland chronology, 6 – Warmia-Mazury chronology, 7 – Suwałki region chronology

Somewhat lower similarity values *t* = 7.7–8.8 were noted with the pine chronologies for Northern Poland and Germany (Saxony and Thuringia). The similarity of the Małopolska fir chronology with the North-Polish pine standard amounts to *t* = 8.86. The heteroconnection value in the case of the German chronology is a little bit lower (*t* = 7.73), which is probably caused by bigger distance between Małopolska and Saxony and Thuringia than the North of Poland, and, consequently, more different climatic conditions.

The shorter (400-year-long) chronologies from Warmia and Mazury and Suwałki region display the values *t* in the range of 6.6–5.6. Lower values of the similarity of the pine chronologies from NE Poland with the Małopolska fir standard are due to different climatic conditions ruling in that part of Poland (higher influence of the continental air masses) as well as their length.

In the case of Gotland, where the growth conditions of the trees are different (the island), the similarity of the Małopolska fir chronology with the pine one amounts to *t* = 5.523, being the lowest among the chronologies compared (Table 5).

Table 5

Comparison of the newly created fir chronology with accessible regional pine standards from adjacent areas (heteroconnection)

| Pine chronologies | Małopolska fir chronology | |
|---|---|---|
| | (*T*) | (*r*) |
| Northern Poland<br>(1106–1991 AD) *Pinus sylvestris* | 8.860 | 0.287 |
| Kujawy-Pomerania<br>(1164–2000 AD) *Pinus sylvestris* | 9.832 | 0.324 |
| Warmia-Mazury<br>(1518–2003 AD) *Pinus sylvestris* | 6.652 | 0.291 |
| Suwałki region<br>(1582–2004 AD) *Pinus sylvestris* | 5.693 | 0.295 |
| Gotland<br>(1124–1987 AD) *Pinus sylvestris* | 5.523 | 0.185 |
| Central Germany<br>(924–1985 AD) *Pinus sylvestris* | 7.732 | 0.252 |

The heteroconnection of the Małopolska pine chronology with the fir regional standards from the adjacent areas demonstrated the highest convergence with the Małopolska fir chronology (*t* = 9.811) – the same climatic conditions of the growth of trees of both taxons. Slightly lower values were noted for the standards for Southern Poland (*t* = 8.624) and Southern Germany (*t* = 8.451), and even lower ones (*t* about 7.5) at comparison with the chronologies from Austria and Central Germany. As in the case of the teleconnection of the fir standard with the Czech chronology, the lowest value was obtained; also in the case of the heteroconnection with the Czech fir chronology the value *t* is the lowest, amounting to *t* = 6.232 (Fig. 39, Table 6).

The teleconnection carried out for two newly constructed standards for the fir and the pine demonstrated the correctness of their construction. The geographical extent and the strength of the dendrochronological signal of the fir chronology are very high to the south (the Austrian chronology) and to the west (the Southern Germany chronology) – (*t* above 17). The dendrochronological signal demonstrated by the pine chronology is considerably lower; only in the cases of two chronologies (the Central German and Kujawy-Pomerania) the similarity values expressed with *t*-value are over 10. This confirms the difficult dendrochronological character of this taxon, due to its multiformity and high individual variability.


Fig. 39. Heteroconnection of the Małopolska pine chronology with the European fir standards; 1 – Małopolska fir chronology, 2 – Central-German chronology, 3 – South-German chronology, 4 – East-Austrian chronology, 5 – Czech chronology

Table 6

Comparison of the newly created pine chronology with accessible regional fir standards from adjacent areas (heteroconnection)

| Fir chronologies | Małopolska pine chronology | |
|---|---|---|
| | (*t*) | (*r*) |
| Southern Poland (1106–1998 AD) *Abies alba* | 8.624 | 0.278 |
| Central Germany (994–1921 AD) *Abies alba* | 7.540 | 0.254 |
| Southern Germany (820–1985 AD) *Abies alba* | 8.451 | 0.273 |
| Eastern Austria (977–1997 AD) *Abies alba* | 7.697 | 0.248 |
| Czech Republic (1131–1997 AD) *Abies alba* | 6.232 | 0.208 |

## THE IMPACT OF CLIMATE ON THE CAMBIUM ACTIVITY AND THE ANNUAL GROWTH WIDTH

Formation and shaping of the annual growth rings is largely dependent on the climate conditions prevailing in a given area. The stability of these conditions is affected by the geographical latitude, relief of the terrain, water relationships, as well as the inflow and transformation of the air masses of various origin, connected with the high-pressure and low-pressure circulation (Hess 1968, Niedźwiedź 1981). Poland is situated in an area influenced by the inflows of humid air masses from the Atlantic and dry air masses of the continental origin, which results in a high changeability and diversity of the individual climatic elements. The changeability of these factors is so high, that as many as 28 climatic regions and separate highland areas have been distinguished (Woś 1999). The Kraków area is situated in the Silesian-Kraków climatic region. Within a year, the inflow of the polar-sea air is here prevailing (65% days in a year), which is causing winter warmth and thaws with increased cloudiness and rainfall, as well as cool weather and heavy clouds with abundant rainfall in summer. The polar-continental air inflows more rarely (26% days in a year); in winter it brings coolness and scarce precipitation, whereas in summer – warmth, thunderstorms, and heavy rainfall. In autumn, temperature inversions with abundant clouds and mists are common. The inflows of the tropical-sea, tropical-continental, and Arctic air occur definitely more rarely. The tropical air brings warmth, i.e. heat and sultriness in summer and sudden warming and thaw in winter, whereas the Arctic air causes coolness and lack of precipitation, frequent strong temperature inversions, and generally heavy fall of the temperature (Hess 1968, 1974, Niedźwiedź 1981).

The temperature and rainfall belong to the climate factors mostly affecting the radial growth at trees.

Recognising variability of these two main climatic elements allows for determination of their impact on the trees, although it is not always easy to illustrate, since short- and long-term climatic events, like e.g. cold, frosty winters, late-spring frosts, summer droughts stimulate the beginning of the cambium activity and may be reflected in tree rings of the populations of various tree species in different ways (wider or narrower xylem layers, missing or double rings). Dendrochronological analysis of the relation climate – growth is most often carried out in two ways. The first, simple way consists in analysis of the signature years. They depict the homogeneity of the reaction of trees to the climate and most often they illustrate drastic changes of the main climate factors (temperature and rainfall). The second method consists in using the response function analysis, providing more statistical approach at the relations climate – growth. Application of both these methods allows for more complementary interpretation of rather complicated reactions growth – climate.

**Signature years**

The main factor influencing the cambium activity and formation of the annual growth is the climate. Its impact is sometimes so strong that annual increments at the majority of the individuals in a given year display the same incremental tendency, developing narrower or wider rings with respect to the previous ones. The signature years are different for different taxons; different years are being identified for the fir and the pine, and still different ones for e.g. the oak. This was confirmed by the studies carried out by Schweingruber (1996) and Krause (1992). In the examined period 1900–1986, the beech, fir, and spruce trees growing in the Swiss Central Plateau indicated different numbers of the signature years: 35 at the beech, 27 at the fir, and 19 at the spruce. The studies of various tree species (beech, oak, pine, and spruce) growing in Northern Germany showed that over a period of 100 years the highest number of the signature years appeared at the beech trees; as many as 42 signature years, 38 signatures at the oak and pine trees, and 29 ones at the spruces (Krause 1992). There happened cases of the same reaction to the climatic conditions at various species of trees in a given year, which resulted in the appearance of the signature years. Within 100 years in Northern Germany such convergent signature years at the beech, oak, pine, and spruce happened only nine times; in six cases negative signatures occurred, and in three cases – positive ones (Krause 1992).

A row of studies concerning the relations climate – growth at the pine and fir trees showed that the annual growth depends on the temperature and the rainfall of the vegetation period as well as the preceding year. For both these taxons cold and frosty winters and dry summers are disadvantageous (combinations of these factors in particular), which results in decrease in width of the annual increments. A decreasing trend in tree rings at the fir may be observed when dry summers are followed by frosty winters (Müller-Stoll 1951), as well as when dry and mild winters coincide with dry summers (Wachter 1979). The analysis of fir trees in the Holy Cross Mountains showed that deep falls of the temperature in winters triggered incremental depressions at this species (Feliksik *et al.* 2000). Narrow growth rings at the fir may be due to not only low temperatures in winter or combinations of a frosty winter followed or preceded by a dry summer, but also extreme droughts in summer, because it is a taxon of the highest requirements as to the air humidity (Puchalski and Prusinkiewicz 1975, Eckstein *et al.* 1983). Decrease of the increment width at the fir is also caused by late, spring frosts, which damage the developing young shoots and suspend the cambium activity (Jaworski and Zarzycki 1983).

The radial growth at the pine is negatively influenced by low temperatures at the end of winter and in early spring (Feliksik and Wilczyński 1998), and also abundant precipitation at the end of summer (September) (Wilczyński 1999). The Scots pine is a species broadly tolerant to the temperature, which is confirmed by its occurrence in natural sites, where the temperature drops below minus 60°C. The minimal temperatures seem to be for the pine of higher importance than the maximal ones.

Pine chronology

In the pine chronology, 57 signature years were distinguished in the course of nine centuries. The highest numbers of the signature years were noted in the sixteenth and fifteenth centuries, twelve and nine, respectively, whereas the lowest figures appeared in the twelfth (three), and seventeenth century (two signatures) (Fig. 40). Among the identified years, the negative signatures were prevailing (33), whereas the positive ones were less frequent (24). Only in two centuries the positive signature years were prevailing; in the fifteenth and eighteenth centuries. In the thirteenth and seventeenth centuries the numbers of the negative and positive years were the same. Any attempt at the explanation of the causes would be very difficult for the majority of the signature years, on account of the fact that systematic instrumental meteorological observations started in Poland only at the end of the eighteenth century. For Kraków, the record of the average monthly temperatures starts from the year 1792 (Wnęk 1999).

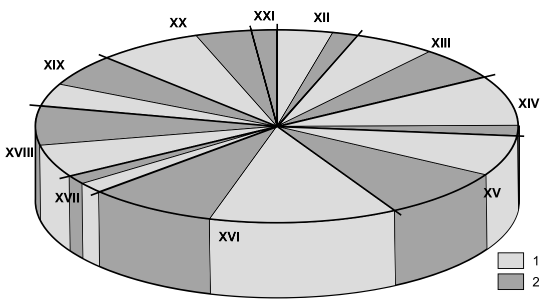


Fig. 40. Negative and positive signature years in the following centuries in the pine chronology: 1 – negative signatures, 2 – positive signatures

The negative signature years in 1880, 1894, 1928, 1940, 1956 were caused by frosty winters. It was so, e.g. in 1880, when the average monthly temperature in December 1879 was minus 9.4°C and in January 1880 – minus 4.1°C. An example of the exceptionally severe winter is the year 1940 when the average temperatures of January and February were exceptionally low; minus 11°C and minus 9.2°, respectively. The cold and frosty winter brought about the negative signature year in 1956, when peculiarly low temperatures occurred in February (the monthly average minus 11.2°C).

The year 1956 deserves a special attention, because in February, within only twenty-four hours, the temperature fell down as far as about 16°C, which resulted in the signature year at the pine trees from the south of Poland. That year the negative signature was also noted in the incremental sequences of the firs from Switzerland (Schweingruber 1996). The year 1956 is a signature not only for the pine from Małopolska; also the oak trees in this region reacted with narrowing of the annual growths, and – as a result of harsh climatic conditions – in the surroundings of Przemyśl the oak trees developed included sapwood (Krąpiec 1998).

The older signature years may be attempted to interpret on the basis of the information from the accessible historical sources, though sometimes they happen to provide ambiguous data (Girguś and Strupczewski 1965).

In the sixteenth century, in which the highest number of the signature years (twelve) was noted, out of which as many as seven were negative, in three cases an explanation of the causes of their formation could be attempted. In 1510 started a very harsh winter, which lasted until April 1511 (Limanówka 2001). Low temperatures in winter and at its end had an adverse influence on the start of the cambium activity and formation of the annual growth at the pine trees, causing the narrowing, which could be observed in 1511. In 1534, the next disadvantageous year, abundant snowfall appeared, under which branches of trees extensively broke, and the winter was very frosty (Limanówka 2001). In April and May the snow melting brought about a flood. The frosty winter was followed by wet summer with frequent downpours. The rainfall was so intense, that at the beginning of July one of the Kraków bridges, leading to Kazimierz, fell down (Girguś and Strupczewski 1965, Brazdil and Kotyza 1997). These adverse weather conditions resulted in the narrowing of the tree rings in 1534. In 1538, however, periods without falls appeared; in March the drought lasted through the entire month, there was not any single day with rainfall, and then, in June great heat came (Limanówka 2001). The droughts in both these months, March and June, could have been responsible for the negative signature year 1538. The analysis of changeability of thermal-precipitation conditions in the period 1501–1840, carried out by Przybylak *et al.* (2004), showed, that the highest number of the extreme summer or winter seasons was noted just in the sixteenth century. Hence, presumably, such a high number of the signature years appeared at that time.

Another century, which was plentiful in appearance of the signature years (nine), was the fifteenth century. The fact that eight of them happened in the second half of the century (the years 1453–1495) merits attention. Such an accumulation of the signature years was brought about by the adverse climatic conditions which ruled then; the years 1450–1465 and 1469–1490 are mentioned in historical sources as the periods of particularly severe, long winters and sharp winds (Malewicz 1980).

Negative signature years provoked by cold and frosty winters in the fourteenth, fifteenth and eighteenth centuries are the years 1363, 1460, and 1784. The negative signature in 1363 was caused by adverse conditions in the winter 1362/63; 'In Poland winter was very harsh, so harsh that the animals perished of hunger, and the wolves – of cold'... It was preceded by untypical summer 1362, when in June 'frost and bad weather appeared' (Girguś and Strupczewski 1965, Brazdil and Kotyza 1997). The year 1460 merits attention as the year in which occurred not only the frosty and severe winter 1459/60, in which the Baltic Sea froze, but the preceding year also diverged from the average, with abundant downpours and floods in March (Girguś and Strupczewski 1965). This tangle of the adverse weather conditions triggered formation of the narrower growth in 1460.

In the course of 900 years, 24 positive signature years were identified in the chronology presented. Müller-Stoll (1951) already remarked that the positive signature years have lower significance for dendrochronology than the negative ones, since they do not yield so much information as the negative signatures. The interpretation of the positive signature years came across more considerable problems than in the case of the negative ones. In 1285, wider growth at the pine trees in the Małopolska region could be a release reaction after the cold and frosty winter in 1284 (Girguś and Strupczewski 1965). The positive signature in 1475 was most probably connected with a very humid summer with frequent downpours, which caused floods, among others in the Kraków area ("...in Kraków and in its surroundings the rains continuously falling the day and night caused immemorial and terrible overflow of the river Vistula. The waters flooded Kazimierz, Stradom and all suburbs..., in churches ... the water reached all the way to the altars..."). Also in Silesia '...that summer was much rain, high water...' as well as in Central Poland, in the environs of Warsaw great floods took place. A similar cause provoked the signature year in 1495 when in the middle of the summer heavy rains caused flood '...higher than the human memory knows, exceeding with the abundance of waters earlier floods...' (Girguś and Strupczewski 1965).

Formation of the positive signature year in 1533 may be explained with abundant rainfall and downpours in July, which led to the flood (Girguś and Strupczewski 1965). The year 1957 is an example of a positive signature year, which came as releasing after a negative one. Low temperatures in February 1956 caused formation of narrower increments at pine trees, whereas favourable weather conditions in 1957 enabled the trees releasing the stress.

The signature years identified for the Małopolska pine chronology, both positive and negative ones, were compared with the signature years from the North-Polish pine standard constructed by Zielski (1997). It turned out that the two almost thousand-year-long chronologies share only four signature years: 1460, 1495, 1928, and 1940. In 1460, the narrow annual growth, noticeable in both standards, was caused by the exceptionally harsh winter in Poland (Girguś and Strupczewski 1965). Two other negative signature years 1928 and 1940 were also related to the influence of frosty winter months. The year 1495 is a negative signature in the North-Polish chronology, and at the same time positive in the Małopolska standard. A low number of the signature years shared by both pine chronologies confirms the previous view that, on the account of high climatic separateness of the South and the North of the country, the reactions of the pine trees to the drastic changes of climate were different.

The signature years of the Małopolska pine chronology were also compared with the signatures from the Małopolska chronology for the oak (Krąpiec 1998). Even though the coniferous and deciduous species have different climatic requirements as regards their growth, the number of agreeable years for these two sequences is higher, amounting to six, than in the case of the pine chronologies for the South and North of Poland. For the pine and oak standards, four shared negative years were recognised (1192, 1256, 1361, 1940), and one agreeable positive year in 1533. Beside these mentioned above, the year 1188 merits attention, having been a signature year shared for the oak and the pine, but the reactions of these two species were opposite. For the oak the year 1188 is a positive signature, whereas for the pine – a negative one. Unfortunately, the available source materials do not yield any description of weather phenomena from that period, which could explain different reaction of these two taxons. Formation of the positive signature in 1533, shared by the oak and pine trees from Małopolska, could be brought about by abundant rainfalls which led to the flood in the first half of that year (Girguś and Strupczewski 1965).

## Fir chronology

The Małopolska fir chronology proved to contain considerably more signature years than the pine chronology; as many as 120 such years were determined (Table 7). The distribution of the signature years in the individual centuries is relatively uniform (except the initial 12th, and the last 21st century), ranging from eleven to sixteen signatures. The exception is the thirteenth century, in which as many as 21 signature years were distinguished (Fig. 41). The negative signature years (67) overbalanced the positive ones (53). Only in four centuries the positive signature years did prevail; in the twelfth, thirteenth, seventeenth, and nineteenth centuries. That prevail was low, amounting to one or two years. Frosty and severe winters were responsible for the negative years: 1205, 1284, 1361, 1440, 1460, 1514, 1537, 1540, 1595, 1608, 1616, 1709, 1731, 1740, 1830, 1872, 1886, 1889, 1920, 1929, 1940, and 1962 (Girguś and Strupczewski 1965, Inglod 1968, Feliksik 1990). The signature year in 1205 was due to the frosty winter 1204/05. The winter was so severe that people left ships trapped in the ice of the Baltic and moved on foot from Denmark to Germany 'having pulled their belongings behind them' (Girguś and Strupczewski 1965).

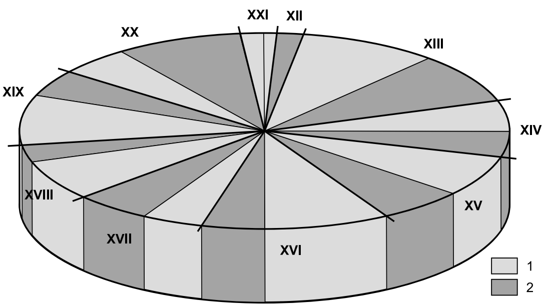


Fig. 41. Negative and positive signature years in the following centuries in the fir chronology: 1 – negative signatures, 2 – positive signatures

Table 7

The signature years in the newly constructed chronologies for the pine and fir trees from the Małopolska region

| Fir chronology | Pine chronology |
|---|---|
| 1172+ | |
| 1187+ | |
| | |
| 1189- | |
| | 1190+ |
| | 1192- |
| 1205- | |
| 1206+ | |
| 1209- | |
| 1218+ | |
| 1220+ | |
| 1224- | |
| 1231- | |
| 1232- | |
| | 1233- |
| 1235- | |
| 1239+ | 1239+ |
| 1241- | |
| 1242+ | |
| 1245+ | |
| 1250- | |
| | 1256- |
| 1264+ | |
| 1270- | |
| 1271+ | |
| 1272- | |
| 1275+ | |
| | 1280+ |
| 1284- | |
| | 1285+ |
| 1290+ | |
| | 1296- |
| 1313+ | |
| 1317- | |
| 1328- | |
| 1331+ | |
| 1332- | |
| 1333- | |
| 1334+ | |
| 1361- | 1361- |
| | 1362+ |
| | 1363- |
| 1372- | 1372- |
| 1374+ | |
| | 1379- |
| 1383+ | |
| | 1388- |
| 1403- | |
| 1414- | |
| 1417- | 1417- |
| 1425+ | |
| 1431- | |
| 1440- | |
| 1441+ | |
| 1445+ | |
| 1453- | 1453- |
| 1456+ | |
| 1459+ | |
| 1460- | 1460- |
| 1461+ | |
| | 1467+ |
| 1471+ | |
| | 1474- |
| | 1475+ |
| | 1478+ |
| | 1481+ |
| 1491- | |
| | 1495+ |
| 1509- | |
| | 1511- |
| 1514- | |
| 1522- | |
| | 1525- |
| | 1526+ |
| | 1533+ |
| | 1534- |
| 1537- | |
| | 1538- |
| 1540- | |
| 1548+ | |
| 1557- | 1557- |
| | 1558+ |
| 1573- | |
| 1575- | 1575- |
| | 1576+ |
| 1579+ | |
| | 1590+ |
| 1592+ | |
| 1593- | 1593- |
| 1594+ | |
| 1595- | |
| 1596+ | |
| 1607+ | |
| 1608- | |
| 1609+ | |
| 1611+ | |
| 1616- | |
| 1620+ | |
| 1629+ | |
| 1634- | |
| 1644- | |
| | 1679- |
| | 1680+ |
| 1686+ | |
| 1689- | |
| | 1702+ |
| | 1706- |
| | 1708+ |
| 1709- | |
| 1725- | |
| 1730+ | |
| 1731- | |
| 1740- | |
| 1748- | |
| 1760- | |
| 1761+ | |
| 1768- | |
| 1772+ | 1772+ |
| 1773- | |
| | 1783+ |
| | 1784- |
| | 1789- |
| 1801+ | 1801+ |
| | 1802- |
| 1804+ | |
| 1808- | |

| Fir chronology | Pine chronology |
|---|---|
| 1818- | |
| 1820- | |
| 1826+ | |
| 1830- | 1830- |
| 1847- | |
| 1856- | |
| 1872- | |
| 1873+ | |
| 1880- | 1880- |
| 1886- | |
| 1889- | |
| | 1894- |
| 1899+ | |

| Fir chronology | Pine chronology |
|---|---|
| | 1911- |
| 1916+ | |
| 1919+ | |
| 1920- | |
| 1925+ | |
| | 1928- |
| 1929- | |
| 1935+ | |
| 1940- | 1940- |
| 1945+ | |
| 1947- | |
| | 1956- |
| | 1957+ |

| Fir chronology | Pine chronology |
|---|---|
| 1959+ | |
| 1961+ | |
| 1962- | |
| 1965+ | |
| 1976- | |
| | 1977+ |
| 1996- | |
| 1997+ | |
| 2000- | |
| | 2002+ |
| 2003- | |

In 1886, low temperatures (below zero) persisted in all winter months: December 1885, January, and February, with the lowest in February 1886 – minus 5.6°C. In March of that year the temperature was also low; the monthly average amounted to minus 2.6°C. Similarly low temperatures, below zero in winter months, were noted in 1889 and 1929. In 1929, February was peculiarly cold; the average monthly temperature amounted to minus 13.2°C (Wnęk 1999).

Relatively accurate data about the climatic conditions in the first half of the sixteenth century in Kraków can be found in the study of Limanówka (2001). Thanks to them it is possible to explain some of the signature years more precisely. For example, the negative year 1514 was caused by strong frosts, which were so severe that caused losses in people, orchards, and the game. Long winter started already in November 1513 and persisted until April 1514; the snow was noted during 72 days. Another negative signature year in that century occurred in 1522. The negative reaction of the fir trees was caused by droughts lasting from July till September 1521, as well as by cool, humid May in 1522, when there were noted 18 cool days and 21 days with rainfall. The attention should be also paid to the year 1540, about which we have exceptionally much information in Polish and European historical sources; it is often described as 'the year of the great drought'. It is known that during six months there was very little rainfall, the heat persisted from May to September, and the rain was noted in only 17 days. The dry summer in 1540 was preceded by an early winter 1539/40, which started in November with harsh frosts, lasting for 21 days, but without snowfall (Limanówka 2001). This disadvantageous tangle of the weather conditions provoked the negative reaction of the fir trees, expressed in formation of narrow growth rings.

Apart from frosty winters, droughts prevailing in summers have also the adverse influence on radial growth of the fir (Girguś and Strupczewski 1965, Inglod 1968, Jasnowska 1977), and they could be a possible explanation of narrow growths in the years: 1332, 1573, 1575, 1689, 1773, 1847, and 1976. Moreover, frosty winters followed by dry summers could have triggered negative reaction at the fir trees, in the form of narrow increments, as it happened in 1760, 1880, and 1947. The fir is a species which is sensitive to the late, spring frosts, causing freezing of young, developing shoots (Jaworski and Zarzycki 1983), which most probably provoked formation of the negative signature years in 1768, 1818, and 1820 (Inglod 1968).

On the other hand, positive signature years at the fir are bound with humid periods. Abundant summer rainfall, or even floods appeared in the years: 1459, 1548, 1579, 1772, 1804, 1997, and they could cause positive signature years. Wet summers preceding the vegetation periods (Girguś and Strupczewski 1965 1965, Inglod 1968, Brazdil and Kotyza 1997) are most probably responsible for the signature years in: 1313, 1459, and 1620, as well as in 1961 – in July 1960 the total monthly rainfall amounted to 262 mm (Wnęk 1999). Wet and mild winters followed by warm springs and summers, with the rainfall in the norm, could have brought about formation of positive signature years in, e.g. 1873, 1916, 1925, and 1961 (Jasnowska 1977, Feliksik 1990). In 1916 and 1925, the average monthly temperatures for the winter months (December–February) were above zero degree, and in February 1925 the average monthly temperature amounted to 4.4°C.

Positive signature years were also often caused by releasing the fir trees to the adverse climatic conditions, which ruled in the previous year; that could happen, for instance in 1919, when the summer 1917 was poor in rainfall, and the following winter was very severe at the turn of 1917 and 1918. The rainfall below the standard value also appeared during the vegetation season in the summer 1918 (Feliksik 1990). The interpretation of the remaining signature years, both positive and negative, is ambiguous.

The signature years determined for the Małopolska fir standard were compared with the signature years of the regional chronologies constructed for Southern Poland (the South-Polish fir standard, the Małopolska pine chronology, and the Małopolska oak chronology). The highest number of agreeable years was stated in the case of the South-Polish fir standard (36), including 26 negative signatures and 10 positive ones. The highest numbers, eight shared years appeared in each of the sixteenth, eighteenth and twentieth century, whereas the least, only one signature, in the thirteenth and the fourteenth centuries. For the Małopolska pine and fir chronologies, 14 shared years were identified (1239, 1361, 1372, 1417, 1453, 1460, 1557, 1575, 1593, 1772, 1801, 1830, 1880 and 1940), including eleven negative and three positive ones. The years shared for the oak and the fir from Małopolska are: 1271, 1275, 1313, 1317, 1332, 1334, 1361, 1456, 1573, 1595, 1731, 1940, with the negative years prevailing (seven).

Two negative signature years merit attention: 1460 and 1940. The year 1460 is an agreeable negative year for two pine standards and two fir ones. It was caused by the severe and frosty winter, about which the historic sources report that '... from Gdańsk to Hel the supplies were directed through the salty sea on the ice ... and those from Hel told that ... as far as the human eyesight could reach, there was nothing but the ice, it was not possible to recognise any water.' The transport on the ice of the Baltic also took place between the German and Swedish towns. Crossings the Vistula River also took place on the ice, '...because the winter was bitter and it was possible to cross the Vistula on the ice...' (Girguś and Strupczewski 1965). The signature year 1940 was stated in all the compared standards for the pine, fir, and oak. It was caused by the harsh winter with prolonged frosts.

Analysing the signature years for the pine and the fir it is possible to state that the fir is a species which is more sensitive for climatic conditions different from the norm, especially harsh and frosty winters with frosts lasting in the spring, as well as dry, hot summers. It is reflected in the number of the signature years, which is considerably higher in the case of this taxon, amounting to as many as 120.

Comparing the signature years in the pine chronologies from South and North of Poland, it should be stated that the reactions of trees growing in these areas are substantially different, which is reflected in the number of the signature years shared (only four agreeable signatures). This points to climatic differences between these regions.

**Relations annual growth – climate (response function)**

Climatic conditions of individual months affect the formation of annual growths to a different degree; especially the average temperature and rainfall have the deciding significance. The relations annual growth – climate were examined through the dendroclimatic analyses, with the response function method.

Scots pine (*Pinus sylvestris*)

The relations between climate and annual growth at pine trees were investigated in various parts of Poland (Zielski 1997, Wilczyński 1999, Feliksik *et al.* 2000, Cedro 2004). Dendroclimatic analyses carried out for pines from North-Western Poland (monthly temperatures and rainfall in the period 1948–1998) showed that in this region the width of the annual growth of the pine and the cambium activity in the vegetative season positively depended on:

- the temperature of the winter months (January, February) and the beginning of spring (March, April),
- the rainfall in January, February, May, June, and July.

On the other hand, high temperatures in July, August and September of the year preceding the vegetation season negatively affected formation of the tree rings (Cedro 2004).

In the vicinity of Toruń (record of climatic data from the period 1861–1991) it was slightly different; the deciding positive impact on formation of the annual growth was exerted by the thermal conditions of February and March and the rainfall in June and July (Zielski 1997). In the Holy Cross Mountains, similarly as in the vicinity of Toruń, the annual growth at pine trees depends on the temperatures in February, and particularly in March (Feliksik *et al.* 2000). Comprehensive dendroclimatic studies based on 62 sites in the Primeval Forest of Białowieża, the Holy Cross Mountains, and the Sandomierz Basin (Wilczyński 1999) showed that the annual growth at pines positively depended on high temperatures in October of the previous year, winter months, and March preceding the vegetation season. Negative effects, however, were due to high temperatures of summer months preceding the vegetation period and spring in the current year.

The analysis response function, carried out for the pine trees from Małopolska, demonstrated, that the annual growth is substantially determined by the temperature of the winter months, February and March, with a stronger impact of the latter (cf. Fig. 42). The correlation coefficient for these two months is significant, taking high values; 0.46 for March and 0.39 for February. Somewhat lower values were obtained for the response function; the multiple regression coefficients reached statistically significant values (at $\alpha = 0.05$) for the temperatures of February and March (0.18 for February and 0.35 for March). The temperatures of the remaining months of the vegetation period as well as the months preceding that period do not have significant meaning for the annual growth. In the case of the rainfall, the values of the correlation coefficient and the response function do not demonstrate any statistically significant relations with the amount of the monthly sum of precipitation, the values of both these parameters are low, around 0.25. This indicates, that neither rainfall from June to December of the year preceding the vegetation season, nor rainfall from January to September of the current year have a decisive impact on the size of growth.

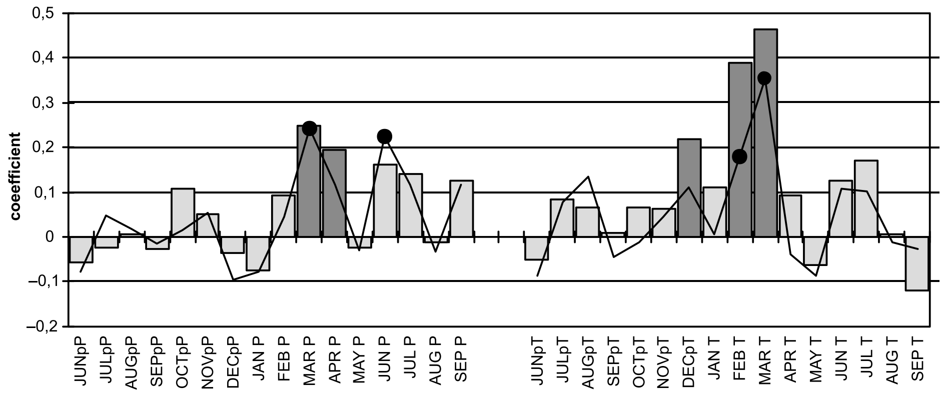


Fig. 42. The response function (broken curve) and the correlation function (columns) for the data from Kraków, the period 1881–1999, *Pinus sylvestris*, significant values at the level 0.05 marked with dark columns and circles

Comparing the results of the response function analyses carried out for the Scots pine in North-Western Poland, the vicinity of Toruń, the Primeval Forest of Białowieża, the Holy Cross Mountains, the Sandomierz Basin, and the environs of Kraków, it is possible to notice that in all these cases formation of the annual increments was strongly influenced by the temperature of winter months, first of all by positive effects of warm February and March. High temperatures of these two months bring about formation of wide radial growths, regardless the region of Poland.

In the case of other tree species growing in the mountain areas the situation looks differently. Dendroclimatic analysis carried out for spruces from the Hala Gąsienicowa by Kaczka (2004) demonstrated the connection of the annual growth with the temperature of two summer months: June and July; however, like in the case of the pine trees from Małopolska, statistically significant relations between growth and rainfall were not observed.

The temperature and rainfall are unquestionably responsible for the beginning of the cambium activity and the width of the xylem layers produced. Dendroecological analyses carried out demonstrate, however, that the impact of the industrial pollutants on the formation of the increments is by no means without meaning, especially in the period of the last sixty years (Szychowska-Krąpiec 1997b, Krąpiec and Szychowska-Krąpiec 2001). The studies demonstrated that the influence of the industrial pollutants was visible both in pine tree stands of the Primeval Forest of Niepołomice (ca. 20 km east from Kraków) as well as at pines from the Ojców National Park (ca. 20 km north from Kraków). Reductions in annual growth rings appeared in the 1950s and 1960s, and a peculiarly disadvantageous period appeared in the years 1970–1990, when reductions of the growth width were drastic, about 70%, and long-term (Szychowska-Krąpiec 1997b, Krąpiec and Szychowska-Krąpiec 2001). In order to check how the air pollutants influence the relations annual growth – climate, the response function analysis was made for two time intervals: 1881–1959 and 1960–1999.

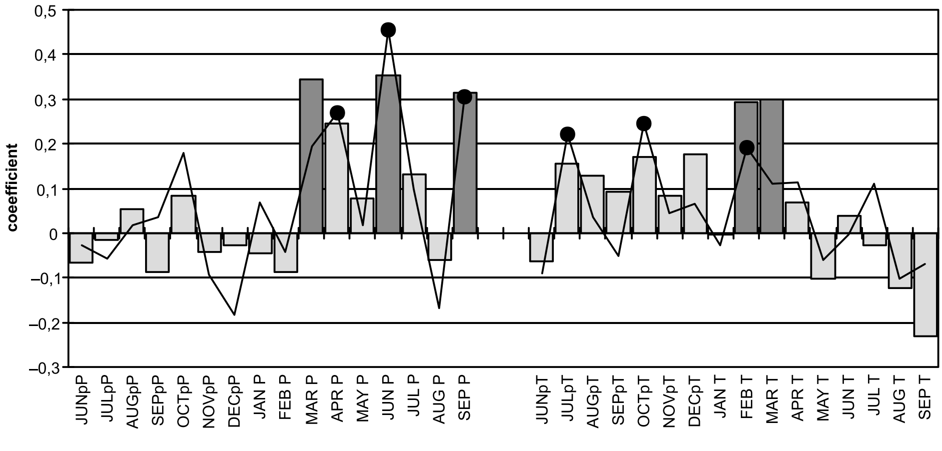


Fig. 43. The response function (broken curve) and the correlation function (columns) for the data from Kraków, the period 1881–1959, *Pinus sylvestris*, significant values at the level 0.05 marked with dark columns and circles

In the years 1881–1959, when the development of the industry was relatively modest, distinct, statistically significant relations appear above all between the growth and the rainfall (Fig. 43). The response function reaches peculiarly high values in the vegetation season for the rainfall in June (0.45), considerably lower for the monthly rainfall in

September and April (0.31 and 0.27, respectively). The correlation coefficient, however, gains similar values for three months: June, March and September (0.35, 0.34, and 0.31, respectively). The rainfall in the remaining months of the vegetation season and in the year preceding it do not play any role. For the relation growth – temperature in the considered period statistically significant relations appeared in February and March, the correlation coefficient values amounting to 0.29 and 0.30, respectively. The statistical analyses carried out showed, that in the period 1881–1959, the deciding influence on the tree-ring width has rainfall in June, and somewhat lower – in March/April and in September. As to the thermal conditions, the air temperatures of February and March of the analysed year affect the size of the growth.

In the second examined period 1960–1999 the width of growth definitely depends on the air temperatures of March and February (Fig. 44). The correlation coefficient of these two variables is statistically significant and adopts high values (0.61 for March and 0.50 for February). Somewhat lower values were received for the response function (0.35 for March and 0.24 for February). Except for these two months, which affect the growth in a substantial way, the temperatures of December also influence growth, but considerably lower (the correlation coefficient being 0.27 and the response function – 0.25). There is, however, lack of distinct, statistically significant relation between the rainfall and the annual growth.

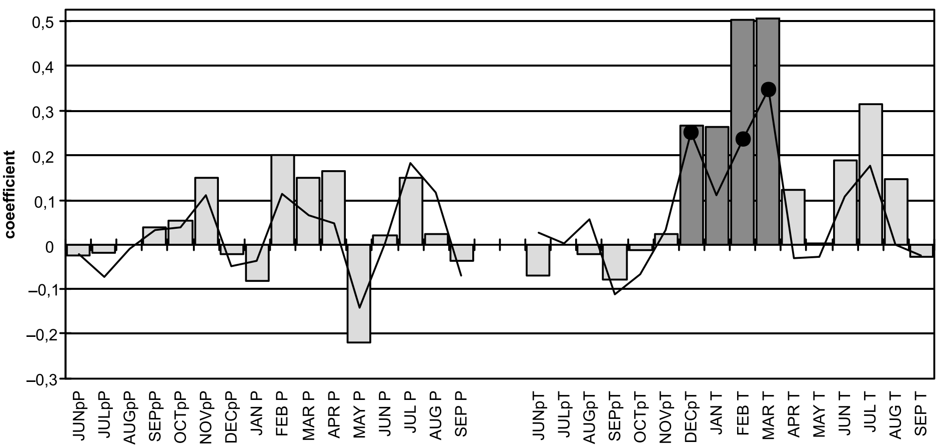


Fig. 44. The response function (broken curve) and the correlation function (columns) for the data from Kraków, the period 1960–1999, *Pinus sylvestris*, significant values at the level 0.05 marked with dark columns and circles

Comparing the impact of the temperature and rainfall on the cambium activity and formation of the annual growths in the periods until 1959 and after 1960, it is possible to conclude that in both these periods the temperatures of February and March are of importance, and in the years 1960–1999 the temperatures of March have higher impact than of February; i.e. differently than in the years 1881–1959, when the temperatures of

February more affected the annual growth. The situation looks totally different in the case of the rainfall; in the period 1881–1959 the rainfall in June, September, and April had an essential impact on the annual growth, but in the years of the rapid industrial development the rainfall did not have statistically significant meaning. Similar relations were observed by von Lührte (1992) at pines growing in the environs of Berlin in the period 1905–1945. There also occurred differences in the relations between annual growth at pines and the temperature and rainfall in the pre-industrial period and the period of the intense industrial development in the years 1945–1986. In the later period the width of growth was mainly affected by the temperature of February and, additionally, the February rainfall.

Silver fir (*Abies alba*)

The response function analysis demonstrated essential statistical relations between the average air temperatures and monthly rainfall and the width of annual growth at fir trees (Fig. 45).

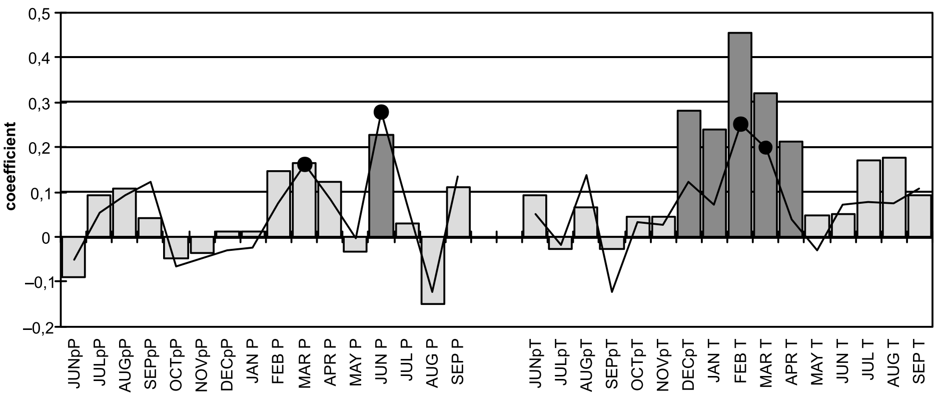


Fig. 45. The response function (broken curve) and the correlation function (columns) for the data from Kraków, the period 1881–1999, *Abies alba*, significant values at the level 0.05 marked with dark columns and circles

The values of the linear correlation coefficients indicate that the temperatures of winter months have a positive effect on widths of annual growth rings, above all the temperatures of February and of March (correlation coefficients 0.46 and 0.32, respectively), and, to a lower degree, the temperatures of December and January. Results of the response function are a little bit humbler, but also statistically significant (at $\alpha = 0.05$) – 0.25 for February and 0.20 for March. For the remaining monthly temperatures significant statistical relations were not stated. The correlation coefficient as well as the response function indicate that, in the case of the temperature, the size of growth at the fir trees depends above all on the thermal conditions of February March, and, to a lower degree, of December and January.

Regarding the rainfall, however, the statistical relations are lower, significant only for one month. Only the rainfall of June of the current year demonstrate the influence on formation of growth rings at fir trees. The correlation coefficient amounts to 0.22, and the response function display even a higher value – 0.28. The rainfall in the remaining months, both in the vegetation season and the preceding year, remain without much importance. Based on both the correlation coefficient and the response function one can clearly see that the conditions in the past do not significantly affect development of a tree ring in the current year. Analysing the obtained results of the statistical analyses one should state, that the formation of annual increments at the fir trees in the Kraków region is influenced by thermal conditions of winter months: February and March, and also by the rainfall in June of the current vegetation season.

The studies of fir trees growing in Polish lowland sites, carried out by Feliksik (1990), also pointed out a decisive effect of the February temperatures on the dimensions and development of the annual growth rings. Apart from the temperature of February also the temperature of January was of importance. Additionally, significant meaning for the annual changeability of tree-rings widths at the firs growing in lowland had the temperatures of other winter months; November and December of a previous year, as well as March of the current year. The results obtained show high sensitivity of the fir to low temperatures in winter.

The analysis of the annual increments of the fir trees from the Holy Cross Mountains demonstrated similar relationships; positive relations with the thermal conditions of February and March. Warmth in these months triggered positive reaction of cambium which could put wider layers of the xylem. The statistical analyses indicate that the xylem production was also positively affected by higher than average values of the summer temperatures, i.e. from June till August, but lower temperatures of May. Warm September, however, exerted a negative impact on the growth size (Feliksik *et al.* 2000).

As in the case of the pine, also for the fir the response function analysis was additionally made for two periods, 1881–1959 and 1960–1999, in order to examine how the climate/growth relations could depend on the industrial pollutions.

In the first period 1881–1959 essential relations between the winter temperatures and the width of annual growth were observed (Fig. 46). Absolute width of the annual growth most strongly depends on the air temperature in February. The correlation coefficient is statistically significant and it adopts a high value 0.54. Similar result was obtained for the response function (at $\alpha = 0.05$) – 0.35. The relation between the growth width and the temperature for remaining winter months, December, January, and March is lower. The correlation coefficient of these two variables is statistically significant and it adopts similar values; 0.38 for December, 0.32 for January, and 0.30 for March. The response function also takes similar values; 0.25 for December and 0.24 for January. For March the response function value is minimal (0.05). However, in the case of the rainfall the tree-ring width is positively correlated with the rainfall in April and September. The correlation coefficients for these two months display the same value of 0.30, also the response function values are close, though slightly lower than the correlation coefficient; 0.23 for September and 0.21 for April. The results of the analyses carried out show that the size of the annual growth of the Kraków fir trees in the years 1881–1959 exclusively depend on the conditions ruling in a given year, whereas the conditions in the past do not affect the size of the tree rings in any significant way.

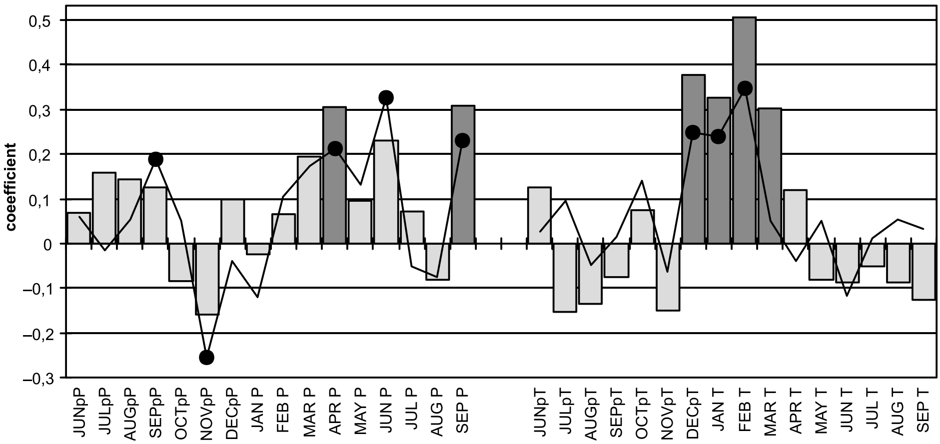


Fig. 46. The response function (broken curve) and the correlation function (columns) for the data from Kraków, the period 1881–1959, *Abies alba*, significant values at the level 0.05 marked with dark columns and circles

The reaction of the fir trees in the period 1940–1999 looks a little bit different; without so distinct positive correlation of the annual growth width with the temperatures of winter months. Dendroecological studies carried out on firs growing in the surroundings of Kraków (the Ojców National Park) demonstrated that, as early as in the 1950s, a decreasing trend of the tree-ring width could be observed; this trend became stronger in the years 1970–1980 and culminated in 1980–1985 (Krąpiec and Szychowska-Krąpiec 2001). These long-term reductions in growth had their impact on the relations growth-climate especially at the fir, which is regarded as the taxon most sensitive to the industrial pollution (Keller 1978). The relations obtained allow to state that the size of the annual growth mostly depends on the temperature of February, for which the correlation coefficient value is the highest (0.46); lower values of the correlation coefficient are observed for March and August (0.36 and 0.38, respectively; Fig. 47). The other factors (air temperatures in January, April, or July), in spite of higher values of the correlation, are not statistically significant. Unfortunately, the response function values are not statistically significant, neither for a single month of the current year nor for any of the preceding year. In the case of the rainfall there is no statistically significant connection between this factor and the width of tree rings.

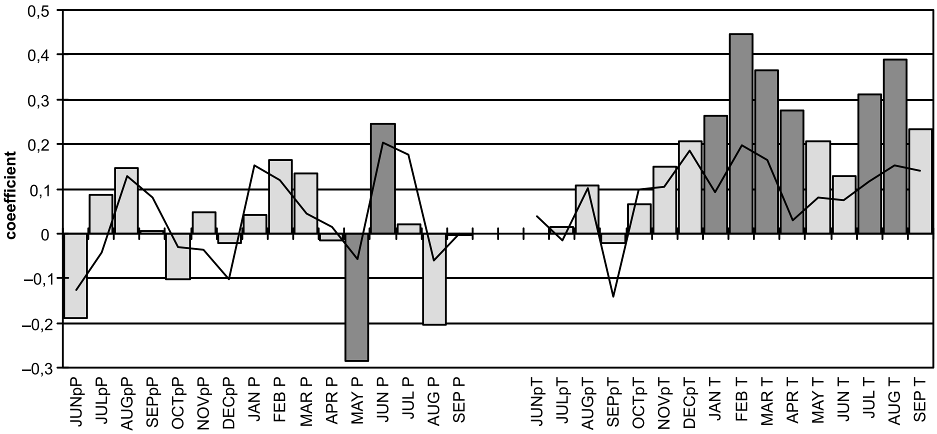


Fig. 47. The response function (broken curve) and the correlation function (columns) for the data from Cracow, the period 1960–1999, *Abies alba*, significant values at the level 0.05 marked with dark columns and circles

The cambium activity and, subsequently, the size of the annual growth of pine and fir trees undoubtedly depend on the climate factors, the temperature and rainfall in particular. Application of two different but complementary methods, the analysis of signature years and the response function, allows for determination of their impact.

The response function analysis showed that the size of the xylem layers produced at fir trees in the forthcoming vegetation season is definitely conditioned by thermal conditions of four winter months: December, January, February, and March. Low temperatures of these months negatively affect the width of annual growth, often resulting in creation of negative signature years. In the case of the fir, the width of the xylem zone formed is additionally influenced by late spring frosts, which are also responsible for appearance of negative signature years. The response function analysis confirms this with the values of the multiple regression coefficient; mild, warm March is positively correlated with the tree-ring width. Similar results of the response function, as in the case of the Kraków firs, were obtained at the relations growth – temperature and growth – rainfall for fir trees growing in the Dinaric Alps in Slovenia, where the annual growth is more dependent on the temperature than the rainfall. The fir trees growing there prefer mild winter, warmer than the average, and humid and cool summer (Schichler *et al.* 1997). Additionally, the temperature and rainfall in September of the previous year, preceding the vegetation period, were significant.

In the case of the pine, similar relationships, strong influence of the February and March temperatures on the annual growth, occur in the Czech Republic, regardless whether the growing sites be drier or more humid (Mácová 2008). Such relationships, however, no longer occur at annual increments of pines growing within the planes and heights of Central Germany. In that region, the rainfall has the determining and predominating impact on the annual growth, whereas the temperature – to a lower degree (Spurk 1997).

Although the influence of the climatic factors is indisputable, accurate presentation of the relations annual growth – climate is very difficult, on account of the fact that the increments widths carry in themselves various elements of other events, such as e.g. insect gradations, forest fires, volcanic explosions, or the effects of the human activity, such as industrial pollutants.

The influence of the industrial pollutants is manifested with reductions or even disappearance of annual growth rings. Most often it is a long-term process of the reduction of tree-ring widths, lasting from a dozen or so till several tens of years. On the contrary, narrow growth rings triggered by the climate factors are usually limited to one or at most a few years. Having compared the relations growth/climate in two periods of time, before and during the rapid industrial development, one can state that these relations are different. In the period 1960–1999 the influence of the pollutants caused weakening of the relation annual growth – rainfall at both fir and pine. At both the tree species studied statistically, essential relations rainfall – growth did not occur in any of the analysed months. On the other hand, the February and March temperatures proved to be of considerable influence. In addition, mild February affected the annual growth at the Kraków firs slightly more than warm March. At the pine the situation is opposite, warm March is better correlated with the growth width than February.

## RECONSTRUCTION OF CLIMATIC CONDITIONS IN THE MAŁOPOLSKA REGION ON THE BASIS OF THE CHRONOLOGIES ESTABLISHED

The response function analysis, the results of which were described in the previous chapter showed that the size of annual growth at fir and pine trees in the Małopolska region was mostly influenced by thermal conditions of winter months. Thanks to these relations, the newly constructed fir and pine chronologies for Małopolska can be used for climatic reconstructions. Usually, in dendroclimatic analyses those versions of the chronologies are used, which are deprived of individual changeability brought about by factors other than climatic and display common features of the given population. They are most often standardized chronologies, obtained after applying the program ARSTAN. In order to check, which version of the chronology correlates best with the climatic factor (the temperature and rainfall), correlation of all versions of the real chronology and the standardized ones were made. Fig. 48 shows these relations for the pine. Similarly as in the response function analysis carried out, the highest values of the correlation, expressed with the correlation coefficient r, were obtained for the sequences standardized with monthly temperatures of February and March, and among them, for the residual sequence ($r$ = 0.37 and $r$ = 0.44, respectively). Analogous operation was carried out in the case of the fir. Fig. 49 presents correlations occurring between monthly temperatures and monthly rainfall and the real and standardized chronologies. Also in this case, the highest r values were obtained for the residual chronology and the temperatures of the winter months (December – $r = 0.24$, Janualy – $r = 0.30$, February – $r = 0.33$, March – $r = 0.43$). Therefore, for further reconstructions residual chronologies were used.

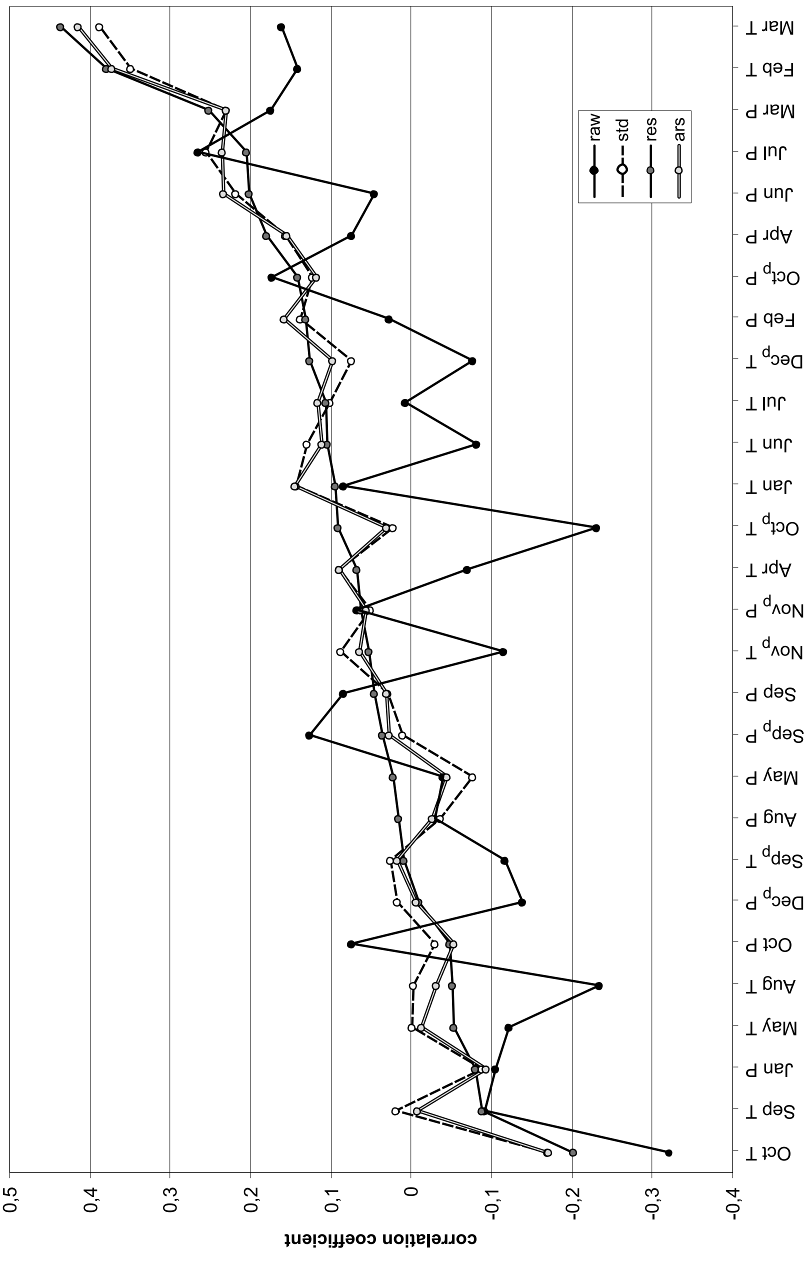


Fig. 48. Correlation of the real pine chronology and its standardized versions with the average monthly temperatures and rainfall in the end of the year preceding the vegetation season (September–December) and the current vegetation year (January–December)

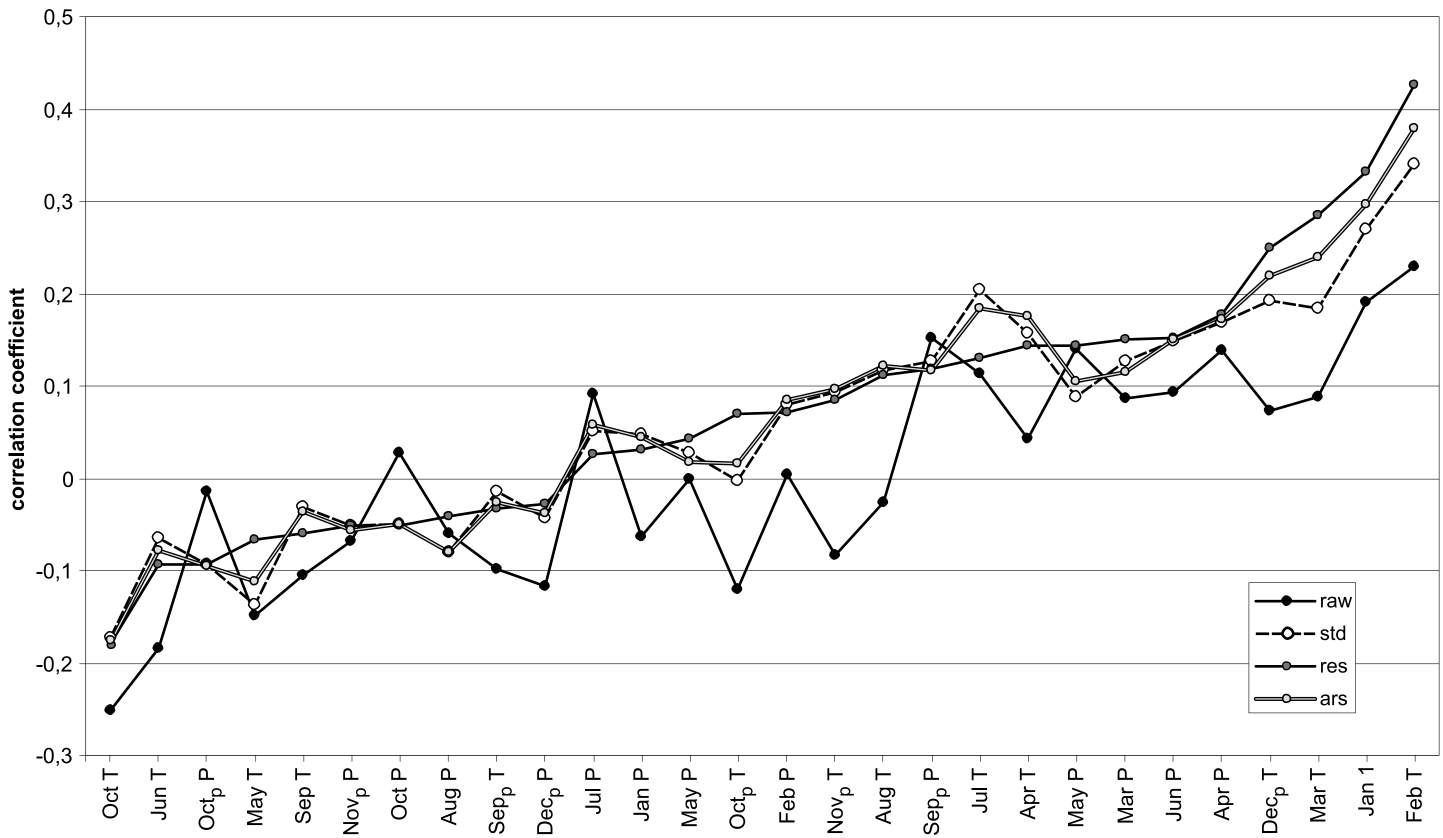


Fig. 49. Correlation of the real fir chronology and its standardized versions with the average monthly temperatures and rainfall in the end of the year preceding the vegetation season (September–December) and the current vegetation year (January–December)

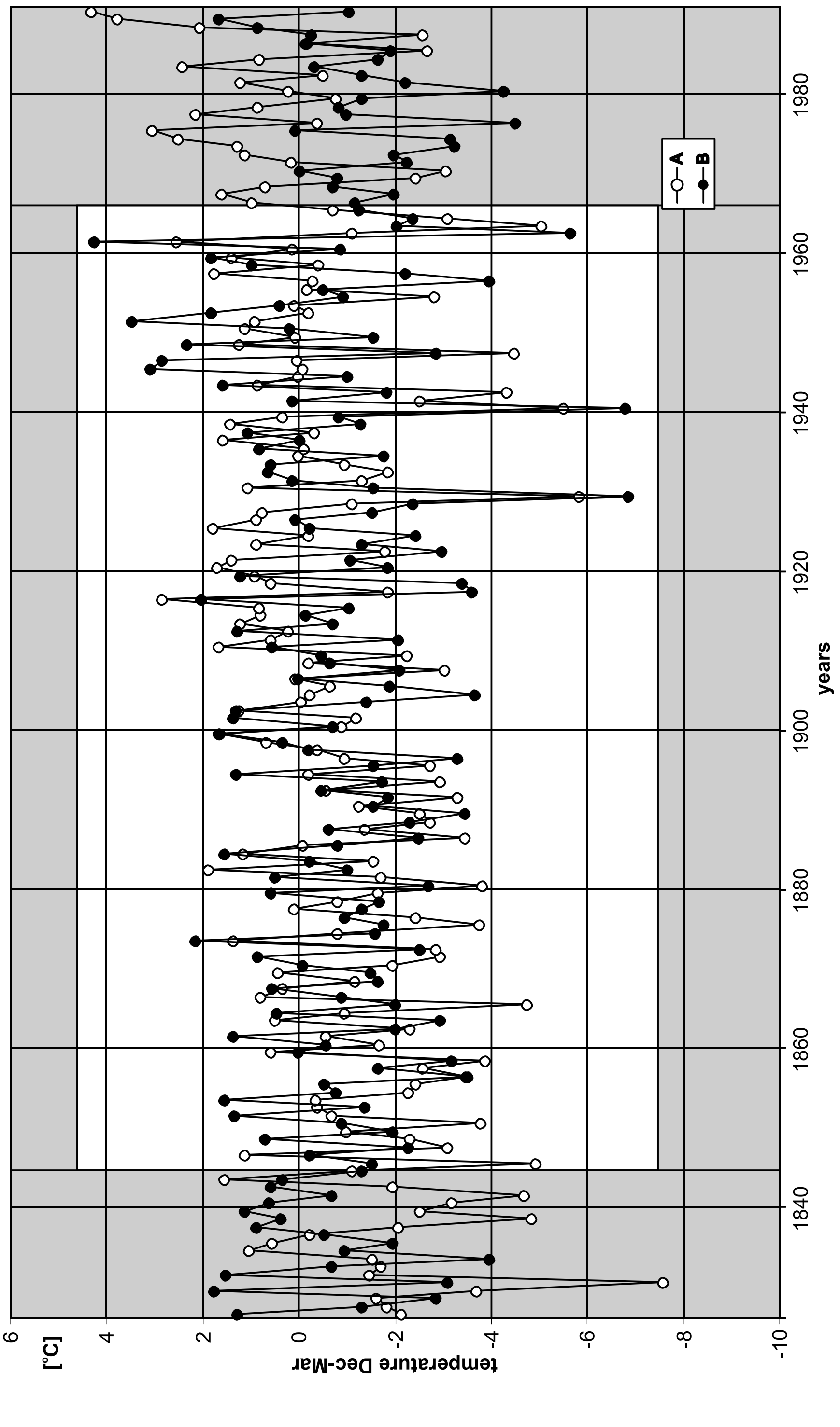


Fig. 50. Comparison of the average monthly temperatures of December, January, February, and March, measured in the period 1827–1990, and the reconstructed temperatures for December, January, February, and March on the basis of the fir chronology: a – temperatures measured, b – temperatures reconstructed

Fir sequence

Correlation analysis was applied for determination of the relations occurring between the residual values of the fir chronology and average temperatures of four winter months (December, January, February, and March) for the Małopolska region. Based on the results of the growth/climate analyses, a transfer function was calculated based on a linear regression model, using the pre-whitened mean winter temperature as the dependent variable and the regional residual chronology as the independent variable. For the period 1827–1990, the temperatures of four winter months (December, January, February, and March) were reconstructed, which was compared with instrumental measurements of temperatures of these months for the same years. Fig. 50 presents the reconstructed temperature of these months and values of temperatures measured for the same months for the period 1827–1990. The agreement of the course of graphs is different in different periods of time. In the period 1846-1960, big concurrence of both graphs may be observed, in which for low temperatures measured low reconstructed temperatures correspond. Reconstructed temperatures showed the strongest response with the temperatures of December–March ($r$ = 0.57). Table 8 demonstrates exemplary values of temperatures measured (measurement data averaged from two stations) and reconstructed for the signature years. It is possible to notice that the temperatures reconstructed demonstrate similar values and the similar trend; to lower values of the temperature measured correspond lower values reconstructed, and to higher ones – the higher temperature values. One should remember, however, that the reconstruction of the December–March temperatures carried out is rather of qualitative character than closely quantitative.

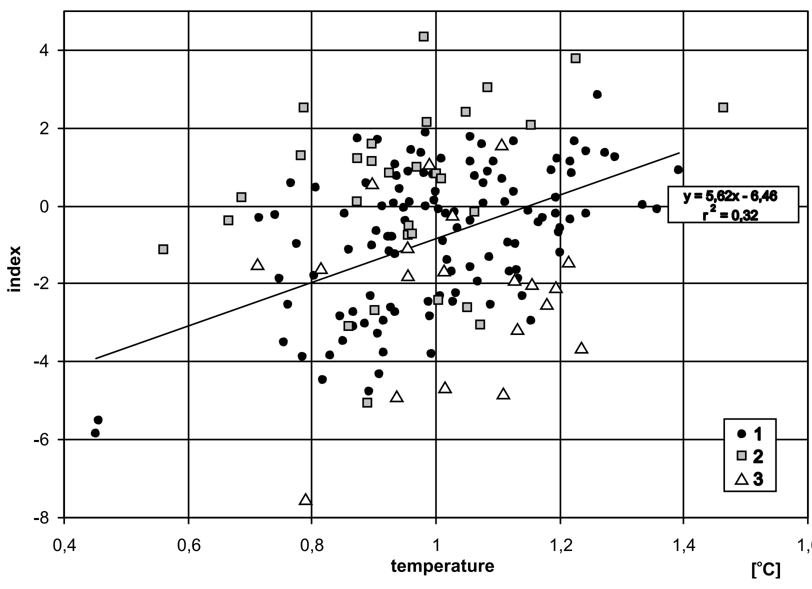


Fig. 51. Scatter diagram of the values of the residual fir chronology indices and the temperatures of four winter months (December, January, February, March) measured in three periods of time: 1 – 1846–1960, 2 – 1961–1990, 3 – 1827–1845

Table 8

The average temperatures measured of four winter months (December, January, February, and March) for Kraków (measurement data averaged from two stations) and the temperatures reconstructed for the signature years of the fir chronology

| Year | Temperature measured (°C) | Temperature reconstructed (°C) |
|---|---|---|
| 1830 | –7.57 | –3.09 |
| 1847 | –3.1 | –2.29 |
| 1856 | –3.52 | –3.52 |
| 1872 | –2.85 | –2.52 |
| 1873 | 1.35 | 2.15 |
| 1880 | –3.82 | –3.71 |
| 1886 | –3.47 | –2.49 |
| 1889 | –2.52 | –3.46 |
| 1899 | 1.63 | 1.63 |
| 1916 | 2.85 | 2.02 |
| 1919 | 0.9 | 1.21 |
| 1920 | 1.70 | –1.86 |
| 1925 | 1.75 | –0.22 |
| 1929 | –5.89 | –6.87 |
| 1935 | –0.13 | –0.81 |
| 1940 | –5.50 | –6.81 |
| 1945 | –0.10 | 3.08 |
| 1947 | –4.47 | –2.85 |
| 1959 | 1.40 | 1.81 |
| 1961 | 2.52 | 4.25 |
| 1962 | –1.12 | –5.66 |
| 1965 | –0.72 | –1.26 |
| 1976 | –0.4 | –4.52 |

Certain divergences of the temperatures reconstructed with respect to the instrumental measurements appear in the 18 initial years (1827–1845) and the last 29 years (1961–1990). This is illustrated by a scatter diagram of values of indices of the chronology and temperatures of four winter months, in which three periods of time were distinguished: 1827–1845, 1846–1960, and 1961–1990 (Fig. 51). The rate of correlation achieves the highest value for the period 1846–1960 ($r$ = 0.57); considerably lower for the two remaining time periods: 1827–1845 ($r$ = 0.1), and 1961–1990 ($r$ = 0.33). Explaining of these divergences is difficult. In the case of the 29 last years, low relations between the temperatures reconstructed and measured are probably caused by anomalies appearing in annual growths, and consisting in their reductions. Narrow growths are tied with the recession of the fir in Poland, which increased in the 1960s, with the development of the industry (Jaworski and Zarzycki 1983).

Dendroecological examinations carried out in the surroundings of Kraków show that, in annual growths of fir trees in the last 50 years, reductions triggered by the industrial pollutants occur. They started in the middle of the 1950s, and their culmination came in the 1980s (Krąpiec and Szychowska-Krąpiec 2001). Low correlations in the initial period 1827–1845 are more difficult to explain. It is hard to search for errors in the chronology; the EPS index values (defining the expression of the population signal) amounts to 0.95, which is considerably higher than the minimum, suggested value of 0.85 and proves a high strength of the signal of the population.

On the account of low absolute values of correlation between instrumental measurements of temperatures and the temperatures reconstructed in the initial (1827–1845) and final (1961–1990) periods, these ranges were thrown away and for further research the period 1846–1960 was chosen, in which value of the rate of correlation takes 0.57 out, however $r^2$ = 0.32, i.e. the changeability of the temperature explains 32% of the variance of indices of annual growths.

Reconstruction of climate changes for the last 900 years for the Małopolska region was made using the residual fir chronology as predictor in the form of 20-year Gaussian filter to highlight the overall trends. To the time series of reconstructed temperatures the moving weighted average has been applied, with weights calculated according it the Gaussian curve, with standard deviation $\sigma = 20$ yr. Sample depth, species and composition of the chronology are shown in Fig. 52. Distinct decreasing trends of the curve were found in periods: 1200–1320, 1350–1450, 1490–1530, 1560–1595, 1630–1780, and 1820–1920. Periods with the maximum appeared in the following years: 1130–1200, 1325–1350, 1450–1490, 1530–1560, 1595–1630, 1780–1820, and 1930–1950.

Pine sequence

As in the case of the fir chronology, the pine chronology was treated in the same way. Based on the results of the growth/climate analyses, a transfer function was calculated based on a linear regression model, using the pre-whitened mean winter temperature as the dependent variable and the regional residual chronology as the independent variable.

The reconstructed average temperatures of two winter months, February and March, demonstrate the agreeable course with the instrumental measurements for temperatures of February and March in the entire compared period 1826–1990 (Fig. 53). Therefore, for further reconstructions the entire compared range was used from 1826 till 1990. As in the case of the fir chronology, for which the average temperatures of four months (December, January, February, and March) were examined, also here prediction of temperatures for two months (February and March) had rather qualitative than quantitative character. Fig. 54 presents a scatter diagram of indices of the residual sequence with temperatures of two months in period 1826–1990. The value of correlation of indices of the sequence with temperatures of February and March amounts to $r = 0.43$ ($r^2 = 0.18$).

In order to reconstruct the temperatures of the last 900 years, residual pine sequence covering the years 1091–2006 AD was presented as predictor in the 20-years Gaussian form filter, like in the case of the fir chronology (Fig. 55). It demonstrates decreasing trends in the following periods: 1140–1190, 1220–1320, 1360–1405, 1430–1545, 1570–

1780, 1830–1920, and 1959–1990, and maxima in: 1100–1140, 1190–1220, 1320–1360, 1406–1430, 1545–1560, 1780–1830, and 1930–1950.

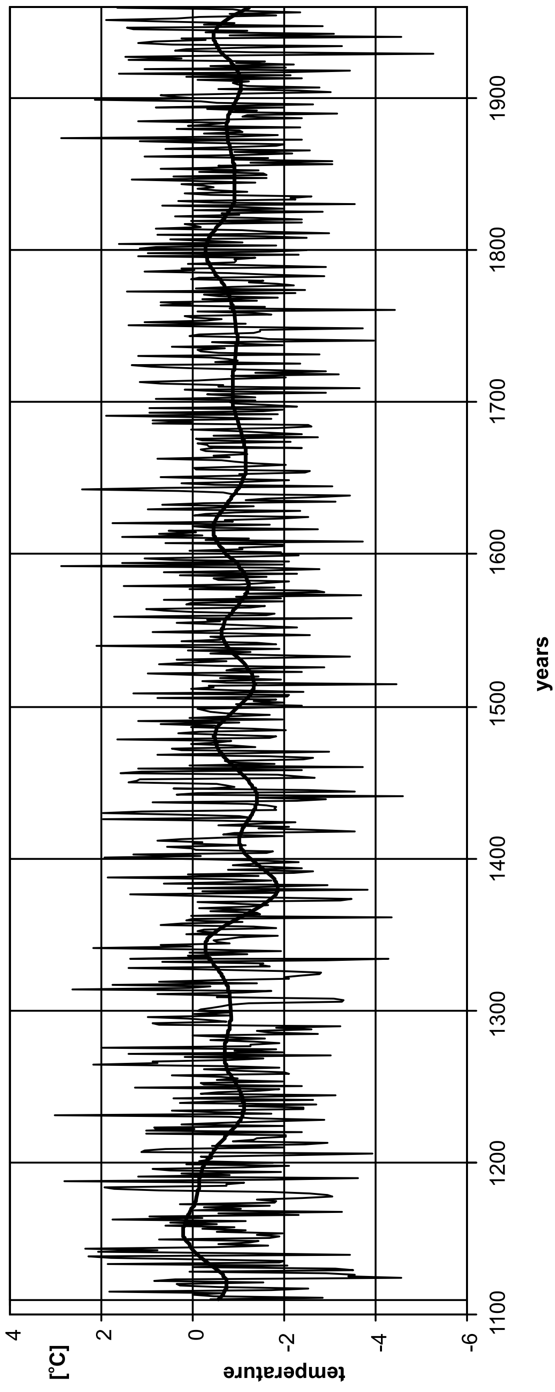


Fig. 52. Reconstruction of the average monthly temperatures for December, January, February, and March on the basis of the residual fir chronology for the period 1109–2004 AD

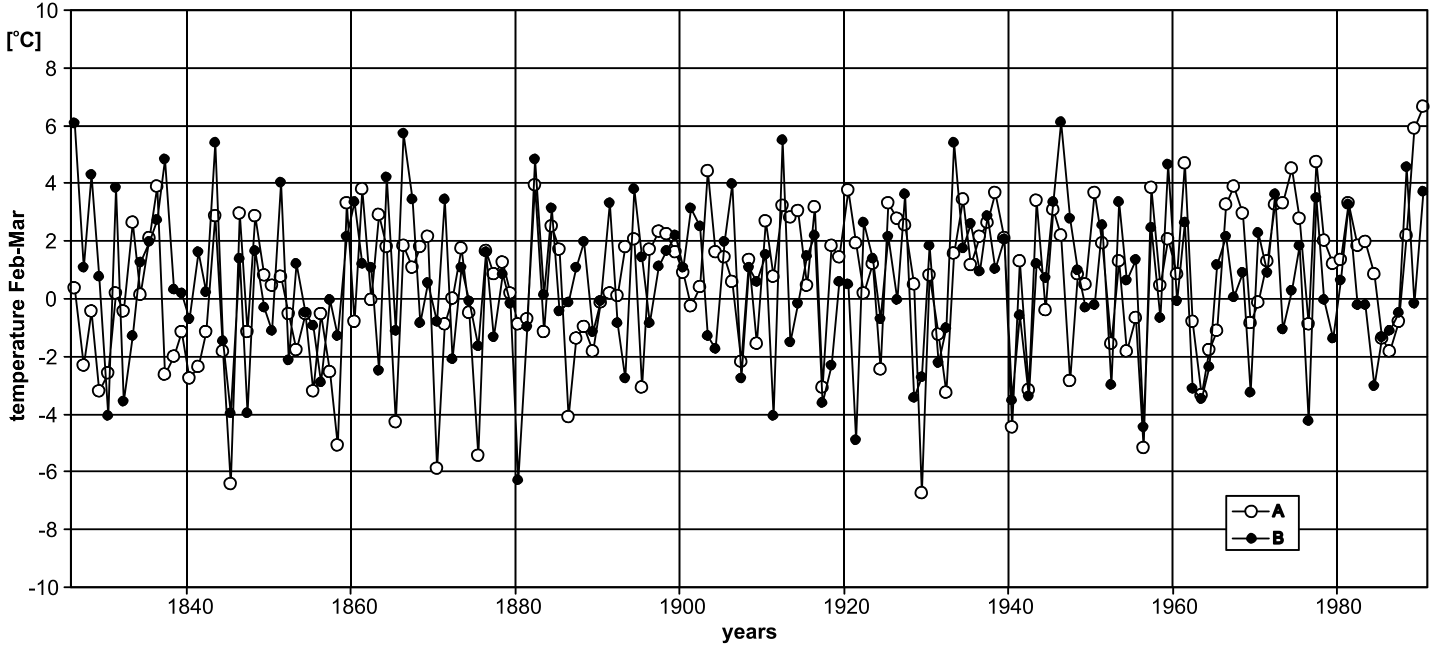


Fig. 53. Comparison of the average monthly temperatures of February and March, measured in the period 1826–1990, and the reconstructed temperatures for February and March on the basis of the pine chronology: A – temperatures measured, B – temperatures reconstructed

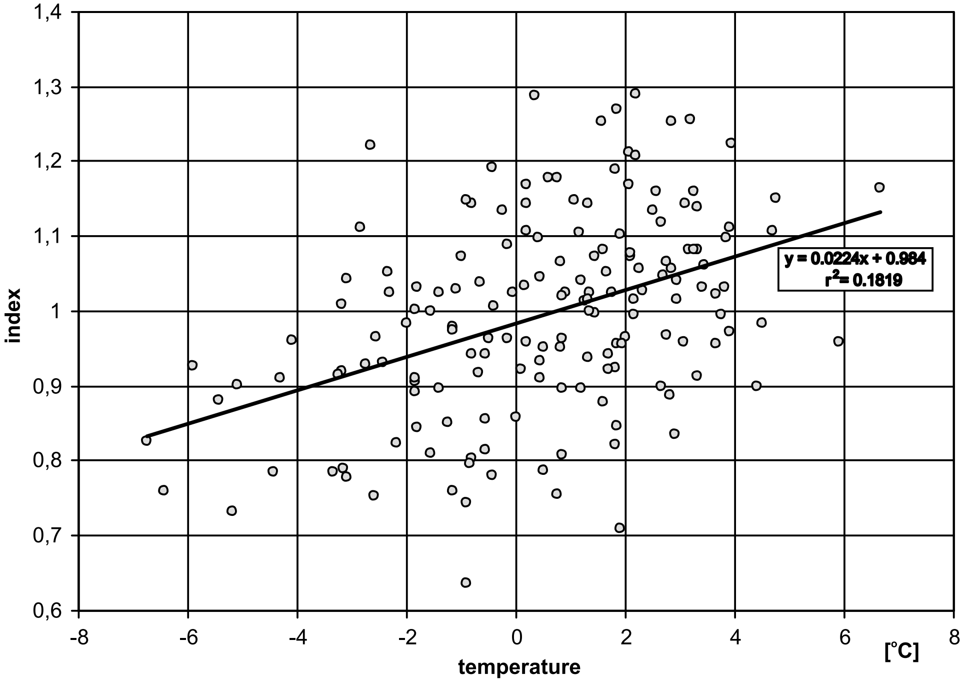


Fig. 54. Scatter diagram of the values of the residual pine chronology indices and the temperatures of two winter months (February and March) measured in the period 1826–1990

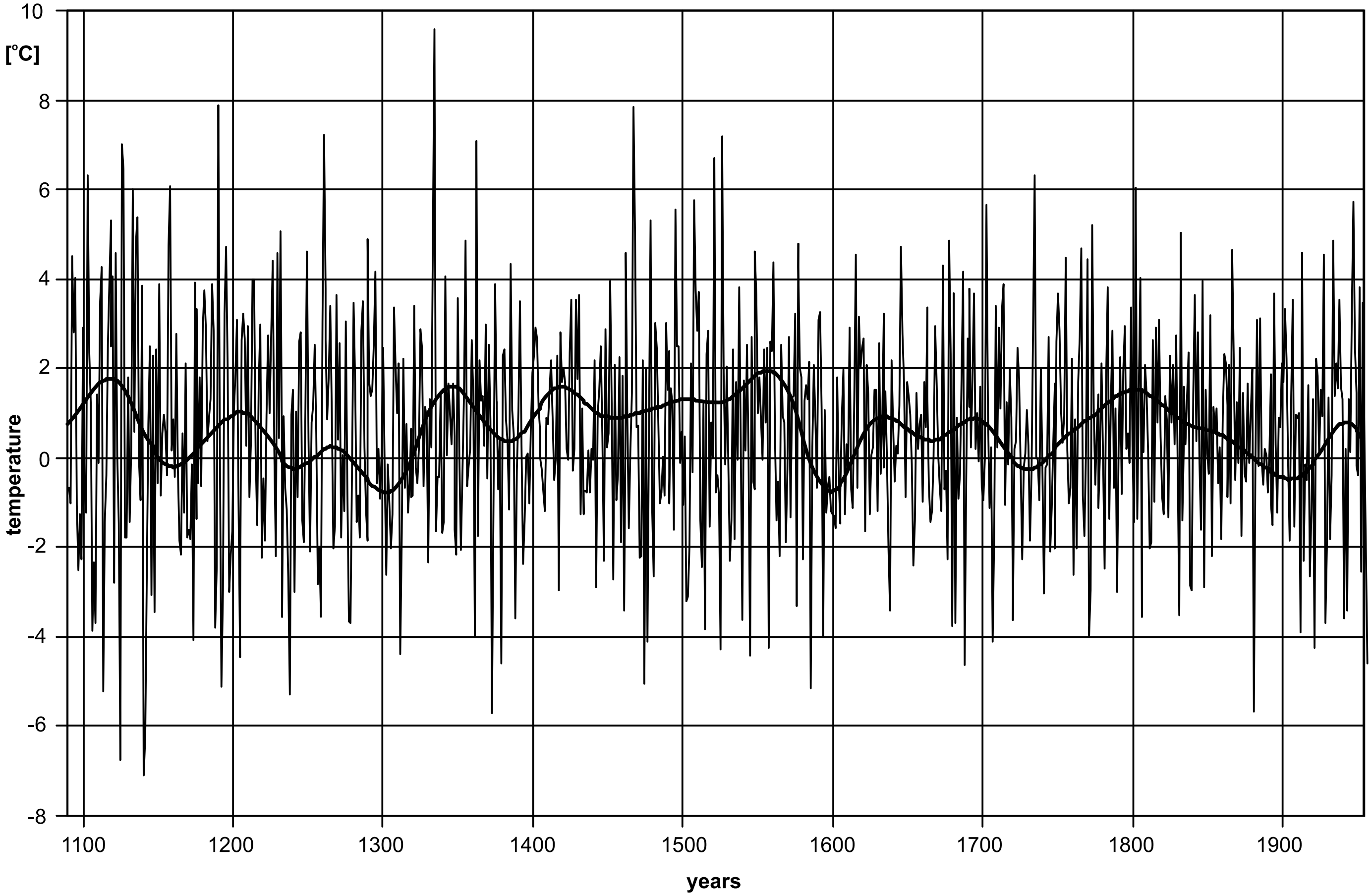


Fig. 55. Reconstruction of the average monthly temperatures for February and March on the basis of the residual pine chronology for the period 1091–2006 AD

Discussion

Analysing the course of the reconstructed temperatures of winter months for the Małopolska region on the basis of the fir and pine chronologies, it is possible to distinguish two periods of their agreeable course: 1220–1405 and 1780–1960. Decrease of both curves appears in the same time what proves that both temperatures of the end of the winter: February and March, as well as the temperatures initial of winter periods: December January; hence, the entire winter period since December till March were characterized with similar directions of changes.

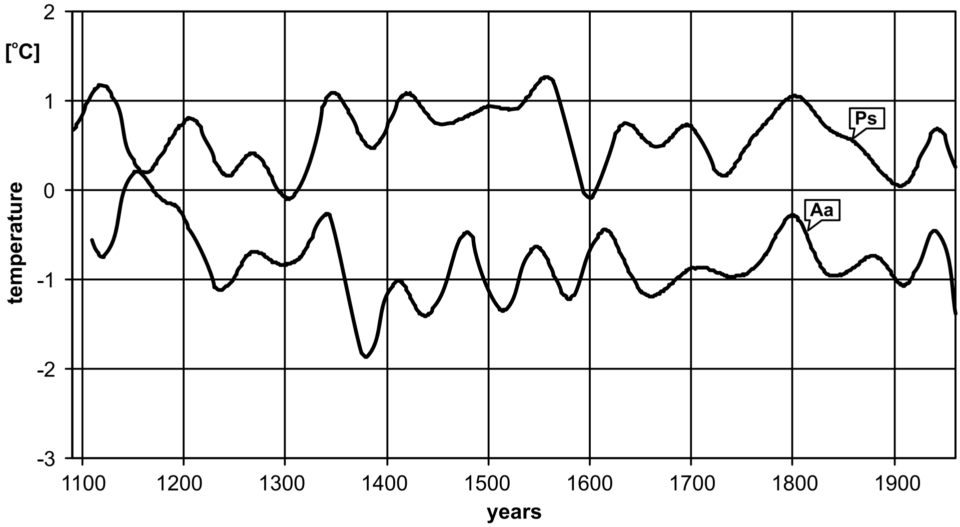


Fig. 56. Comparison of the reconstructed temperatures of December, January, February, and March on the basis of the fir chronology (Aa) and the reconstructed temperatures of February and March on the basis of the pine chronology (Ps)

In the first of the mentioned periods: 1220–1405, it is possible to observe two episodes of the increase in winter temperatures: the first one in 1250–1280 with the maximum about 1270, and the second period, warmer than the previous one, in 1320–1350/60. It is possible to treat the entire period 1220–1405 outside the two mentioned episodes as the period with low temperatures of the winter since December till March, with bigger drops of the winter temperatures from about 1350 till end 1405 with maximum about 1380 (Fig. 56). In the fourteenth century, similar temperatures of the winter as in the Małopolska region appeared in western and central Europe. Reconstructions of the winter temperatures carried out by Pfister *et al.* (1996) show that generally the entire fourteenth century was cool, with a little warmer weather in 1328–1350. The beginning of the fourteenth century is a period of cool winters except one 'warmer' 1303/1304 and two more harsh in 1305/1306 and 1322/1323 in central and western Europe. However, in the second half of the fourteenth century, a cooler minimum about 1375 with exceptionally cool January (average temperature –3°C) in the years 1354/1355 and 1363/1364 was noted (Pfister *et al.* 1996). 25 last years of the fourteenth century do represent in both compared reconstructions a similar period of winter temperatures in the Małopolska region and central and western Europe. The end of the fourteenth century with low temperatures finds expression in source materials concerning Kraków. Analysing graphs of prices of commodities of plant origin in Kraków, it is possible to notice that at the end the fourteenth century just came their height. Of course, the causes of their growth can be found in many sources, as even illnesses, a plague of locusts or floods, but it is not possible to exclude that it could have been triggered by the cooling of the climate, which, as a matter of fact, was suggested by Maruszczak (1999). The rise in prices was noted also in other cities, not only in Kraków, which can render that the cooler weather had the bigger territorial extent (Maruszczak 1999).

In the second period of the very similar course of temperatures reconstructed (1780–1960), it is possible to distinguish two distinct maxima: 1780–1820 and 1930–1950 (Fig. 56). The first of them points at the increase in temperatures of winter months since December till March with the culmination about 1800, when the optimum of this period was marked. The warm turn of the eighteenth and nineteenth centuries was preceded by high negative anomalies of the Little Ice Age in the period of winters in the decade 1771–1780, like those registered in the 16th (1541–1550, 1571–1580, 1591–1600) and 17th (1641–1650, 1651–1660) centuries (Luterbacher *et al.* 2010a,b).

The end of the 18th century was also identified as the warm period in highlands, in the Tatra mountains, the area of Babia Góra and Dolina Gąsienicowa in reconstructions of temperatures of summer months (June and July) on the basis of annual growth of the arolla pine (*Pinus cembra L.*) (Bednarz 1976) and spruce (*Picea abies L.*) (Bednarz 1996, Kaczka 2004).

After this period of warmth, from about 1820 the temperatures reconstructed for winter months on the basis of analysis of growths of the fir and pine from the Małopolska region point to the period of cool winters lasting to about 1920. In this period, years with the lowest annual temperature appeared in Kraków in: 1829 (5.3°C), 1832 (6.6°C), 1838 (5.9°C), 1855 (6.7°C), 1858 (6.2°C), 1864 (6.2°C), 1870 (6.2°C), 1871 (5.7°C), and 1875 (6.6°C) (Wnęk 1999).

After the decreasing trend of both curves lasting for about 100 years, from 1920 to about 1950 the second maximum points to the increase in temperatures of the winter (December–March – the fir and February–March – the pine).

Apart from the two described intervals of the agreeable course of reconstructed temperatures of winter months, such a synchronicity appears no longer in the remaining periods. Definitely low temperatures of February and March, reconstructed on the basis of the pine, merit attention in the period 1570–1780 with two extremes: about 1600 and 1730–1740. The turn of the 16th and 17th centuries with low reconstructed temperatures of the winter appeared outside the Małopolska region also in northern Poland, where, in reconstructions carried out on the basis of annual tree rings of the pine in the Lower Vistula region, the end of the 16th century is characterized by low temperatures of the winter (Przybylak *et al.* 2005). The period 1590–1600 AD was, according to Przybylak *et al.* (2005), characterized by high negative anomalies, about –3°C. The cool winter period about 1600 AD appeared not only in the South and North of Poland. In reconstructions carried out on the basis of instrumental temperature series, together with available field reconstructions of sea-level pressure for the late winter/early spring (January–April) season for different European areas (also Poland), in 1595, 1600, 1601, and 1614 anomalously cool winters took place (Luterbacher *et al.* 2010a,b). A similar period with low temperatures, however, in the summer months was noted in Femundsmarka in north, as well as in central Norway. Also here, peculiarly adverse conditions appeared about 1600 AD, when a very long winter lasted in 1601 since early September by May of the next year (Kalela-Brundin 1999). This period of coolness was noticeable also in the Alps with advance of glaciers: in the French Alps in Rosière surroundings (Ladurie 1972), in Eastern Alps in Őtztal surroundings, and in Swiss Alps with the maximum reach of the Unterer Grindelwald glacier (Grove 1988). A cool period about 1600 AD, appearing in reconstructions on the basis of tree rings of the pine and fir in the Małopolska region, could be correlated with a rise in prices of the food articles of plant origin (oat, pea, barley) in Kraków, what could be associated, i.a. with the cooling of the climate (Maruszczak 1994).

The second episode with very low temperatures 1730–1740, noted in growth of the pine from the Małopolska region, is a well known cold period in Europe, and 1741 is characterized by exceptionally narrow growth of pines in Femundsmarka, broght about by ‘a total frost year’ (Jones *et al.* 1995). The period of coolness in Europe at that time is often tied with weakening of the sun activity, so-called Maunder minimum (1645–1717) (Grove 1988). The period of low temperatures of winter months 1730–1740, reconstructed on the basis of tree rings of the pine from Małopolska, is also noticeable in annual rings of the Tatra arolla pine, which recorded the influence of the continental air with narrow growth; and reconstructions of temperatures of June and July made on this basis confirmed this period of coolness (Bednarz 1976). Comparing the obtained reconstructions of temperatures February/March with reconstructions of temperatures for north Poland on the basis of annual growth of the pine, one can notice that the period of cooler winters appeared there a little bit later, in the years 1760–75 (Przybylak *et al.* 2005). According to ten-year averages of value of air temperatures of the winter (December–February) in Poland in the period 1501–1840, on average the coolest periods appeared exactly in the decade 1741–1750 (anomaly: –3.7°C) (Przybylak 2008). This cold period lasting from the 16th to the 18th centuries is reflected in growth of fir trees, though the course of the reconstructed temperatures from December till March displays other tendencies than the reconstructed temperatures February-March on the basis of the pine. The fir chronology indicates that at the turn of the 16th and 17th centuries, in the years 1595–1630, the episode with warmer winters occurred.

Following the course of reconstructed temperatures of the winter on the basis of the fir chronology one should state that the warmest winters in the last millennium appeared in the years 1130–1200. However, reconstructed temperatures of February and March on the basis of growth of pine trees point out that the warmer period took place earlier, in 1100–1140, and then a phase with cool February and March appeared, which lasted to about 1200. Only in the twelfth century, such different reactions of both species to winter temperatures were noticeable. These differences in reconstructions could have been caused by low replication of both chronologies in their initial periods, especially the pine chronology, which achieved the number of ten samples in 1181, as well as with low value of the EPS coefficient (0.85) of signal defining the expression of the population in the initial period of the pine chronology. In the pine sequence, the EPS reaches a satisfactory value above 0.85 only in the year 1200.

The reconstructed average temperatures of four winter months in the 12$^{th}$ century on the basis of the fir point to warm winters ruling in the Małopolska region in the years 1130–1200. Occurrence of mild winters was also noted in north Poland in the period 1170–1200, on the basis of reconstruction of the average temperature for four months (January–April) basing on annual rings of the pine (Przybylak 2008), which seems to be one of the higher in the course of the last 1000 years. According to Maruszczak (1999), it is exactly the twelfth century which was the warmest century in the entire last millennium, and especially its second half. Reconstructions of temperatures April–August on the basis of annual growth of pine trees from Fennoscandia also show that the second half of the twelfth century was very warm (Briffa 1992).

A period of coolness noticeable in the period of winters in the years 1960–1990, reconstructed on the basis of the pine sequence, merits attention. It does not correspond to the measurement data of temperatures of February and March and the overall characteristics of the climate of Kraków, where in the period of 100 last years in 1948–1972 and in the last 25 years of the 20$^{th}$ century, the warmer weather connected with the growth of oceanic influences appeared (Kożuchowski and Marciniak 1991, Piotrowicz 2007). Analysis of changes in temperatures in Kraków in the last century indicates that the temperature generally increased by about 1.5°C, and the month in which the increase was the highest (2°C for 100 years) was February (Piotrowicz 2003). Among all months, February was also characterized by the biggest changes in temperatures, from –13.2°C in 1928 to 5.6°C in 1990. Among the seasons, the biggest diversities in the examined years concerned winter, for which the time of beginning was more and more late, and the end – more and more early. This caused considerable shortening of the winter period and simultaneous extending of the fore-winter period (Piotrowicz 2007). The warming of winters in Kraków, noted since the 1960s, is not reflected in the reconstructed temperatures of February and March, what suggests that development of the annual growth of pines was dependent not only on temperatures of winter months, but also on other factors. Without doubt, industrial pollutants were one of such factors; emission increased in the 1960s, as it is observed in annual tree rings of pines from the Małopolska region (Krąpiec and Szychowska-Krąpiec 2003, Muter 2004, Danek 2007). In the years 1960–1990, the period of thermal adverse conditions was noticeable not only in the winter period in the Małopolska region; it also appeared in the route of summer period in the area of the Tatra Mountains. The results obtained by Niedźwiedź (2004) for the Tatra Mountains show that in 1960–1990 low temperatures of the summer appeared and this entire period was considered as cool. It was most probably caused (especially in the summer) by appearance of the deepened west circulation as well as the growth of the industrial emission of pollutants into the atmosphere.

The described reconstructions of average monthly temperatures from December till March (for the fir) and from February till March (for the pine) demonstrate shorter periods characterized by adverse thermal conditions lasting for about 40–50 years (1140-1190, 1360–1405, 1490–1530, 1560–1595, and 1950–1990), as well as longer periods of about 100 and over 100-year-long (1200–1320, 1350–1450, 1630–1780, 1830–1920).

Some of the periods indicated above may be linked with the activity of the Sun and the changeable number of solar stains. The weakened activity of the Sun and the low figure of stains correlate with periods of coolness. The minimum of Wolf, noticeable at the turn of the thirteenth and fourteenth centuries (1280–1350), may be tied with the episode of cool winter months December–March at the fir and February–March at the pine in 1280–1320 in the long-term, above secular period of cooler weather in 1200–1320. The cool period noticeable at the turn of the fifteenth and sixteenth centuries (1490–1530) can be correlated with the Spörer minimum (1460–1550), and a 150-year period of cool winters in the seventeenth and eighteenth centuries (1630–1780) with the Maunder minimum (1645–1715) (Fig. 57). The beginning of the Maunder minimum, falling for the year 1645, is clearly noticeable with the low temperatures of December–March in the fir chronology, as well as with the low temperatures of February and March in the pine chronology. In the Late Maunder Minimum, from about 1675, an uptick of examined temperatures is noticed to about 1715, i.e. the end of the Maunder minimum. Similar observation was made in the Tatra Mountains, where the beginning of the Maunder minimum was characterized by low reconstructed temperatures of summer months and the end – with their increase (Niedźwiedź 2010). Following the course of reconstructed temperatures of winter months on the basis of annual growth of the pine and fir from the Małopolska region, one should take notice of the fact that after every minimum, even the enough poorly last minimum of Dalton (1790–1820), a sudden drop of reconstructed temperatures is observed, except the Maunder minimum, the end of which in Małopolska was warmer than the beginning (Fig. 57).

The distinguished periods of cooling are expressed in the outline of climate changes suggested by Lamb (1984): the Mediaeval Climatic Optimum (MCO), Little Ice Age (LIA), and Contemporary Period of Warmer Weather (CPWW), where the Little Ice Age has arisen a lot of controversy but reconstructions of palaeoclimate conducted for LIA often demonstrate substantial differences (Przybylak 2008). According to Lamb (1980), LIA lasted from 1550 till 1850, however Porter (1986) is considerably extending this time, placing the beginning of LIA for 1250 AD and its end for 1920 AD. Also Kotarba (1994), on the basis of a study of lacustrine sediments from the Morskie Oko Lake in the Tatra Mountains, places the end of LIA at the beginning of the $20^{th}$ century. Examinations of cladoceran, chironomid and diatom analyses in the Tatra Mountains are also pointing to the end of LIA at the beginning of the twentieth century (1920s) (Gąsiorowski and Sienkiewicz 2010). In the work of Luterbacher *et al.* (2004), the end of this phase of cool climate is defined for a time postdating 1850 AD, i.e. to the second half of the 19th century. Reconstruction of temperatures of winter months, based on firs and pines from the Małopolska region, suggests that about 1920 the last defined period of cool winters terminated, what is in agreement with the views of Porter (1986).

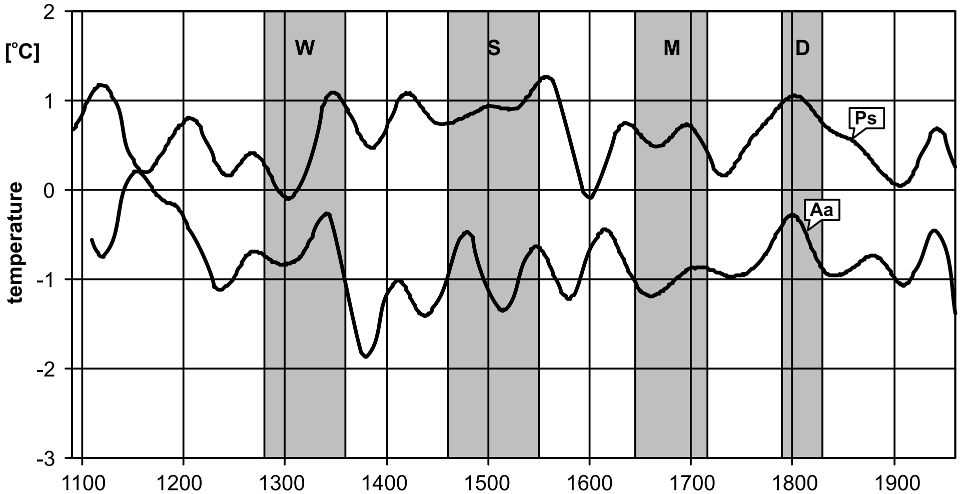


Fig. 57. Comparison of the reconstructed temperatures of December, January, February, and March (Aa) and the reconstructed temperatures of February and March (Ps) with the periods of the weakened solar activity (W – the Wolf Minimum, S – the Spörer Minimum, M – the Maunder Minimum, D – the Dalton Minimum), Ps – the reconstructed temperatures of February and March on the basis of the pine chronology, (Aa) the reconstructed temperatures of December, January, February, and March on the basis of the fir chronology

Beside the periods of particularly adverse conditions in winter months since December till March, the periods were found when temperatures of these months were higher: 1130–1200 (only for the fir), 1100–1140 (only for the pine), 1190–1220 (only for the pine), about 1320–1360 (the fir and the pine), 1406–1430 (only for the pine), 1450–1490 (only for the fir), 1530–1560 (the fir and the pine), 1595–1630 (only for the fir), 1780–1830, and 1930–1950 (the pine and the fir). Warmer weather conditions appearing in the 12th century are connected with the final phase of the Mediaeval Climatic Optimum, which was noticeable in Europe (Lamb 1984) and, like in the case of the Little Ice Age, its limits are controversial. In the western part of Europe, the MCO most probably started in the mid-twelfth century (1150) and lasted to 1300 (Lamb 1984) what, in turn, is not confirmed in reconstructions of the average annual temperatures for the last millennium carried out by Guiot (1992), where one should move the beginning and the end of this phase of warmth to 1200 and 1350. In eastern Europe, however, beginning of the MCO – according to Lamb (1984) – was noticeable considerably earlier, because already in 950 and its end took place in 1200. Still differently the situation was in Fennoscandia, where the beginning of the MCO – according to Briffa (1992) – is placed about the year 1000 and the end about 1300. On the basis of reconstruction of temperatures of winter months (December–March) from the annual growth of the fir, it is possible to conclude that this warm period in the Małopolska region ended about 1200, which is in agreement with the views of Lamb (1984) concerning eastern Europe.

## CONCLUSIONS

This contribution presents the results of dendrochronological studies concerning the populations of fir and pine trees growing in the Małopolska region. The research material was above all historical wood coming from the structures of various wooden objects and from archaeological excavations, as well as wood from living trees. The dendrochronological analysis of over 3,000 samples resulted in establishing two absolutely dated standards: 896-year fir chronology, covering the period 1109–2004 AD, and 916-year pattern for the pine (1091–2006 AD). The Małopolska pine standard is the first such long pine standard for the Małopolska region, and the second constructed in Poland.

The Małopolska fir standard is partly based on the local research material, coming from the Małopolska region, which was exhaustively described by the author in 2000, at presentation of the South-Polish fir chronology. The newly constructed Małopolska chronology permits for enhancing chances of dating individual sequences of fir wood with short individual patterns (30–40 tree rings), which is practically impossible in the case of other tree species, as well as facilitates concluding about the origin of wood, so essential at dating mobile objects.

The studies of the Małopolska standard yielded numerous figures of the absolute dating of a row of wooden structures, from both secular and sacred objects. The dating results indicated or confirmed the time of their building, reconstruction, or repair. There were, among others, numerous historic churches from the Małopolska and Holy Cross (Świętokrzyskie) voivodeships. The analyses carried out yielded dates of building the roof structures of the churches in Chotel Czerwony, Zborówek, Chroberz, Krzcięcice, Strzelce Wielkie, Grabie, as well as the collegiate church in Wiślica. The obtained dates of cutting down the trees, from which, in the cases mentioned above, the structural elements were made, are usually tantamount to the time of their construction. In historic times, wood was most often used as the building material right after cutting the trees down, without any previous seasoning (Holst 1993). Dendrochronological dating also allowed to determine the dates of renovating the roof structures at the churches in Imielno, Szaniec, Kossów, Małogoszcz, Dobrowoda, Nowy Korczyn, Jędrzejów, Górka Kościelnicka, and Wiślica.

The studies also resulted in a row of valuable tree-ring data for the timbers from archaeological excavations, e.g. wooden buildings in the Central Market Square in Kraków, on the western side of the Cloth Hall (Sukiennice) (fragments of mobile stalls and/or stores, elements of wells and water pipes coming from the end of the thirteenth and the middle of the fourteenth centuries), the old stalls and the road pavement in Bytom (the end of the thirteenth century), the structure of the residential buildings in the Market Square in Rybnik (the end of the thirteenth century), and buildings of the Old Town in Wodzisław Śląski (1658 AD, 1816 AD).

Multiple dendrochronological data were produced for wood occurring in the historic salt mines in Bochnia and Wieliczka, dating back to the thirteenth century. The old levels of the mines, exploited in the Middle Ages, still contain wood originating from those times, preserved in the mining galleries and chambers as the elements of wooden casings, various devices, or the mining equipment. The oldest wood in the mine casings was encountered in the Dusząca chamber (1387, 1390, 1405, 1422 AD) and the Goryszowski shaft (1485–1495 AD) in the Wieliczka Salt Mine.

High dating potential of the chronologies newly constructed is confirmed by their similarity with the regional standards for these tree species from Poland and the neighbouring countries. The Małopolska fir chronology exhibits high correlation values with the standards from the areas situated about 1000 km westwards – the South-German chronology (Becker and Giertz-Siebenlist), as well as to the south: the Czech standard (Kyncl and Kyncl) and the East-Austria chronology (Liebert *et al.*) (about 700 km); *t*-values about 17–19. Such high similarity values are typical for this tree species. The fir is characterized with low individual variability, contrary to the pine with its high intra-species changeability. In the case of the pine standard, the highest similarity values were obtained for the 800-year Kujawy-Pomerania chronology (Zielski) ($t = 12.31$) and the Central-Germany standard (Heussner) ($t = 10.78$).

The chronologies presented are not only precise tools for the absolute dating, but they are also natural archives for proxy data, similarly as corals, speleothems, or ice cores used for the reconstructions of the climate in the past. Extreme weather events, such as frosty, long-lasting winters, hot and dry summers, late frosts in spring, or floods may be reflected in signature years. In the course of the last 900 years, as many as 120 signature years were distinguished in the fir chronology and 57 ones in the pine standard. The reactions of the pine and fir to the weather phenomena are different, which is rendered in only thirteen signature years shared (eleven negative and two positive ones). The common negative signature years appear in the period of the evident cooling of the climate, with higher influence of the continental circulation over the territory of Poland, which occurred from the second half of the fourteenth century to about the middle of the fifteenth century (five negative signatures shared), and also in the Little Ice Age (five negative signatures shared). The annual increments represent not only a record of the extreme events, but also a continuous record of the main meteorological parameters, such as the temperature and rainfall.

The studies on the impact of the climate conditions on the cambium activity and the width of the annual growths at the pine and fir demonstrated that at both these species the thermal conditions of two winter months, February and March, are of the highest importance. Warm February and March positively affect the size of the xylem layer formed in the forthcoming vegetation season. Additionally, in the case of the fir, the increment width is negatively influenced by late frosts, appearing in April. At both these species, the impact of the atmospheric rainfall is lower; its certain connection with growth appears, but statistically it is not as much significant as in the case of the temperature.

In the last decades considerable reductions in the width of the annual tree rings have been observed. The pine, but the fir in particular, belong to the taxons, which are most sensitive to the effects of air pollution. The reductions observed are quite a universal phenomenon, appearing not only at the pines and firs in the Małopolska region, but also in other regions of Poland. They are brought about by the industrial pollutants of the air. Most drastic influence of them was noticeable in the 1970s and 1980s, when reductions in the tree-ring widths came even up to 70%. From the 1990s, the situation has considerably improved. Analysing the influence of industrial pollutants on the relations annual growth – climate, one should state that their influence is important for both, the fir and the pine. At the pine, the dependence of the annual growth on the temperature of February and March is varying, and additionally the December temperature gain an essential statistical significance. At the fir, however, beside the temperatures of winter months (December–March), additionally the impact of the temperatures of July and August appears. On the other hand, the rainfall in the period of the intensive industrial pollutions does not play any important role.

The dependence of the annual growths on the temperatures December-March at the fir and February–March at the pine was used for reconstruction of these temperatures in the Małopolska region in the last 900 years. The periods of low temperatures were identified; in the entire winter, from December till March, in the case of the fir, and in two winter months, February and March, in the case of the pine. Low temperatures of four winter months (December–March) appeared in the following periods: 1200–1320, 1350–1450, 1490–1530, 1560–1595, 1630–1780, and 1820–1920 AD. Cool periods February–March were identified in: 1140–1190, 1220–1320, 1365–1405, 1570–1780, 1830–1920, and 1959–1990 AD. Some of the cool periods determined correspond to changes in the solar activity and Sunspot population. The Wolf Minimum (1280–1350) is reflected in the cool episode 1280–1320, which occurred within the long-term, cool period 1200–1320. The Spörer Minimum (1460–1550) could be possibly correlated with the cool episode 1490–1530, indicated by the fir chronology. A long period of low winter temperatures, 1630–1780, indicated by the fir, or 1570–1780 based on the pine, encompasses the Maunder Minimum (1645–1715), with the initial cool phase followed by the somewhat warmer one.

The reconstructed winter temperatures in the Małopolska region as well as the distinguished periods of warmer and cooler winters find expression in the general pattern of the long-term climatic changes: the Mediaeval Warm Period, the Little Ice Age, and the Recent Global Warming. Higher-temperature winters, in 1130–1200 (December-February, based on fir) or 1100–1140 (February–March, based on pine), could be possibly connected with the final phase of the Mediaeval Warm Period. The long-term period of disadvantageous winter temperatures, commencing about 1560/1570, could be interpreted, in turn, as a cooling phase within the Little Ice Age, which terminated in the Małopolska region in the 1920s. Finally, the Recent Global Warming is marked in the conducted reconstructions since the third decade of the twentieth century.

The climatic reconstructions of temperatures of winter months in the Małopolska region demonstrated the distinct periodicity of thermal conditions in the last 900 years. Up to now, these are the first dendroclimatic reconstructions for this region reaching so far back in time.

REFERENCES

Akkemik Ű., Dagdevirent N. and Aras A., 2005. A preliminary reconstruction (A.D. 1635–2000) of spring precipitation using oak tree rings in the western Black Sea region of Turkey. International Journal of Biometeorology **49**: 297–302.

Badowska B. and Kierys A., 2007. Ocena stanu degradacji drzewostanów na podstawie analizy dendroekologicznej z okolic Lgoty (in Polish). Unpublished M.Sc. thesis, Wydział Geologii, Geofizyki i Ochrony Środowiska AGH, Kraków: 73 ms. pp.

Baillie M. G. L., 1995. A slice through time. Dendrochronology and precision dating. Batsford Ltd., London: 176 pp.

Baillie M. G. L. and Pilcher J. R., 1973. A simple cross dating program for tree-ring research. Tree-Ring Bulletin **33**: 7–14.

Bartholin T., 1987. Dendrochronology in Sweden. Annales Academiae Scientiarum Fennicae, Geologica-Geographica **145**: 79–88.

Becker B., 1982. Dendrochronologie and Paläoökologie subfossiler Baumstämme aus Flussablagerungen. Mitteilungen der Kommision für Quartärforschung **5**: 1–121.

Becker B. and Giertz-Siebenlist V., 1970. Eine über 1100-jährige mitteleuropäische Tannenchronologie. Flora **159**: 310–346.

Bednarz Z., 1976. Wpływ klimatu na zmienność szerokości słojów rocznych limby (*Pinus cembra* L.) w Tatrach (in Polish). Acta Agraria et Silvestria, series Silvestria **16**: 3–33.

Bednarz Z., 1987. The 225-year tree-ring chronology of the oak (*Quercus robur* L.) in the Niepołomice Forest near Kraków. Dendrochronologia **5**: 59–68.

Bednarz Z., 1996. June-July temperature variation for the Babia Góra National Park, Southern Poland, for the period 1650–1910. Zeszyty Naukowe Uniwersytetu Jagiellońskiego, Prace Geograficzne **102**: 523–529.

Bednarz Z. and Niedźwiedź T., 1997. Dendrochronologia świerka *Picea abies* (L.) Karst. z Parku Narodowego Wysokie Taury. Unpublished report, 30 ms. pp.

Billamboz A., 2002. Die dendrochronologische Heterokonnexion verschiedener Holzarten am Beispiel der metallzeitlichen Pfahlbausiedlungen Südwestdeutschlands. Aussangen aus paläoklimatischer und – ökologischer Sicht. In: A. Bräuning (Ed.), Zum Stand der Anwendung der Dendrochronologie in der Geowissenschaften. Stuttgarter Geographische Studien **133**: 13-32.

Birrong W., 1988. Statistische analyse des Zusammenhangs ausgewählter klimatologischer und botanischer Informationen im Zeit- und Frequenzbereich. Institut der Meteorologie und Geophysik der Universität Frankfurt/Main **77**: 158 pp.

Boratyński A., 1993. Systematyka i geograficzne rozmieszczenie (in Polish). In: S. Białobok, A. Boratyński and W. Bugała (Eds.), Biologia sosny zwyczajnej. Wydawnictwo SORUS, Poznań–Kórnik: 45–70.

Brazdil R. and Kotyza O., 1997. Kolķsįnķ klimatu v českżch zemķch prvnķ polovinģ na eho tisķciletķ (in Czech). Archeologické rozhledy **49**: 663–699.

Brazdil R., Štépánková P., Kyncl T. and Kyncl J., 2002. Fir tree-ring reconstruction of March-July precipitation in southern Moravia (Czech Republic), 1376-1996. Climatic Research **20**: 223–239.

Briffa K. R. 1992. Dendroclimatological reconstructions in northern Fennoscandia. In: T. Mikami (Ed.), Preceedings of the International Symposium on the Little Ice Age Climate. Tokyo Metropolitan University, Tokyo: 5–10.

Brykowski R. and Kornecki M., 1984. Drewniane kościoły w Małopolsce południowej (in Polish). Zakład Narodowy im. Ossolińskich, Wrocław: 176 pp.

Cedro A., 2004. Zmiany klimatyczne na Pomorzu Zachodnim w świetle analizy sekwencji przyrostów rocznych sosny zwyczajnej, daglezji zielonej i rodzimych gatunków dębów (in Polish). Oficyna IN PLUS, Wołczkowo: 142 pp.

Chernykh N. B., 1996. Dendrokhronologia i arkheologia (in Russian). Rossiyskaya Akademia Nauk, Institut Arkheologii, Izdatel'stvo NOX, Moskva: 1–213.

Chorowska M., 2003. Rezydencje średniowieczne na Śląsku. Zamki, pałace, wieże mieszkalne (in Polish). Wrocław: 181–182.

Cook E. R., 1990. Beschämen conceptual linear aggregate model for tree-rings. In: E. R. Cook and L. A. Kairiukstis (Eds.), Methods in Dendrochronology: Applications in the Environmental Science. Kluwer Academic Publishers, Dordrecht: 98–104.

Cook E. R., Buckley B. M. and D'Arrigo R. D., 1996. Inter-decadal climatic oscillations in the Tasmanian sector of the Southern Hemisphere: evidence from tree rings over the past three millennia. In: P. D. Jones, R. S. Bradley and J. Jouzel (Eds.), Climatic variations and forcing mechanisms of the last 2000 years. Springer-Verlag, Berlin: 141–160.

Cook E. R. and Holmes R. L., 1986. Users manual for program Arstan. In: R. L. Holmes, R. K. Adams and H. G. Fritts (Eds.), Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin. Chronology Series **6**, Laboratory of Tree-Ring Research, University of Arizona, Tucson: 50–65.

Cook E. R. and Peters K., 1981. The smooting spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bulletin **51**: 45–53.

Cropper J. P. 1982. Response functions. In: M. K. Hughes, P. M. Kelly, J. R. Pilcher and V. C. LaMarche (Eds.), Climate from Tree Rings. Cambridge University Press, Cambridge: 47–50.

Čufar K., De Luis M., Eckstein D. and K□-) ( ä -Bogataj L., 2008. Reconstructing dry wet summers in SE Slovenia from oak tree-ring series. International Journal of Biometeorology **52**: 607–615.

Danek M., 2007. The influence of industry on Scots pine stands in the south-eastern part of the Silesia-Kraków Upland (Poland) on the basis of dendrochronological analysis. Water, Air and Soil Pollution **185**: 265–277.

D'Arrigo R. D., Cook E. R., Salinger M. J., Palmer J., Krusic P. J., Buckle B. M., and Villalba R., 1998. Tree-ring records from New Zealand long-term context for recent warming trend. Climate Dynamics **14**: 191–199.

Dąbrowski M. J. and Ciuk K., 1972. Materiały do dendrochronologicznej stratygrafii osady na Ostrówku w Opolu (in Polish). Archeologia Polski **17**: 445–462.

Dąbrowski M. J., Hunicz A. and Kardasz M., 1975. Badania archeologiczne prowadzone na Wzgórzu Zamkowym w Lublinie (in Polish). Wiadomości Archeologiczne **40**: 27–36.

Diaz S. D., Touchan R. and Swetnam T. W., 2001. A tree-ring reconstruction of past precipitation for Baja California Sur, Mexico. International Journal of Climatology **21**: 1007–1019.

Eckstein D., Aniol R. W. and Bauch J., 1983. Dendroklimatologische Untersuchungen zum Tannesterben. European Journal of Forest Pathology **13** (5–6): 279–288.

Eckstein J., Bauerochse A. and Leuschner H. H., 2008. Local or large-scale spatial signal? A research strategy for the dendroecological evaluation of bog pine horizons. Eurodendro 2008, Hallstatt: 78.

Ermich K., 1953. Wpływ czynników klimatycznych na przyrost dębu szypułkowego (*Quercus robur* L.) i sosny zwyczajnej (*Pinus sylvestris* L.). Próba analizy zagadnienia (in Polish). Prace Rolniczo-Leśne PAU **68**: 1-61.

Ermich K., 1959. Badania nad sezonowym przebiegiem przyrostu grubości pnia u *Pinus sylvestris* L. i *Quercus robur* L. Acta Societatis Botanicorum Poloniae **28**: 15–63.

Ermich K., 1960. Zagadnienie telekonekcji w dendrochronologii na przykładzie dębu bezszypułkowego w Bawarii i w Polsce (in Polish). Rocznik Dendrologiczny **14**: 31-43.

Faryna-Paszkiewicz H., Omilanowska M. and Pasieczny R., 2001. Atlas zabytków architektury w Polsce (in Polish). Wydawnictwo Naukowe PWN, Warszawa: 599 pp.

Feliksik E., 1986. Modern chronologies of *Abies alba* Mill. in Poland. In: L. Kairiukstis, Z. Bednarz and E. Feliksik (Eds.), Methods of Dendrochronology. Proceedings of the Task Force Meeting on "Methodology of Dendrochronology: East/West Approaches" – Kraków 1986, Warszawa: 187–193.

Feliksik E., 1990. Badania dendroklimatyczna dotyczące jodły (*Abies alba* Mill.) występującej na obszarze Polski (in Polish). Zeszyty Naukowe Akademii Rolniczej, Kraków **151**: 1–106.

Feliksik E. and Wilczyński S., 1998. Wpływ temperatury i opadów na przyrost roczny drewna świerka, sosny i modrzewia występujących w leśnictwie Pierścień u podnóża Pogórza Wilanowskiego (in Polish). Problemy Zagospodarowania Ziem Górskich **44**: 77–86.

Feliksik E., Wilczyński S. and Podlaski R., 2000. Wpływ warunków termiczno-pluwialnych na wielkość przyrostów radialnych sosny (*Pinus sylvestris* L.), jodły (*Abies alba* Mill.) i buka (*Fagus sylvatica* L.) ze Świętokrzyskiego Parku Narodowego (in Polish). Sylwan **144** (9): 53–63.

Friedrich M., Kromer B., Spurk M., Hofmann J. and Kaiser K. F., 1999. Paleo-environment and radiocarbon calibration as derived from Lateglacial/Early Holocene tree-ring chronologies. Quaternary International **61**: 27–39.

Fritts H. C., 1976. Tree-ring and climate. Academic Press, London, New York, San Francisco: 567 pp.

Gąsiorowski M. and Sienkiewicz E., 2010. The Little Ice Age recorder in sediments of a small dystrophic mountain lake in southern Poland. Journal of Paleolimnology **43**: 475–487.

Girguś S. and Strupczewski W., 1965. Wyjątki ze źródeł historycznych o nadzwyczajnych zjawiskach hydrologiczno-meteorologicznych na ziemiach polskich w wiekach od X do XV (in Polish). Wydawnictwa Komunikacji i Łączności, Warszawa: 214 pp.

Golinowski W., 1971. The anatomical structure of the common fir (*Abies alba* Mill.) bark. I. Development of bark tissues. Acta Societatis Botanicorum Poloniae **40**: 149–182.

Gorczyński T., Molski B. and Golinowski W., 1965. Podstawy dendrochronologii w zastosowaniu do potrzeb archeologii (in Polish). Archeologia Polski **10** (1): 75–110.

Goslar T., 1987. Dendrochronological studies in the Gliwice Radiocarbon Laboratory equipment, first results. Annales Academiae Scientiarum Fennicae, Ser. A. III Geol. – Geogr. **145**: 97–104.

Grove J. M., 1988. Little Ice Age. Chapman and Hall, New York: 498 pp.

Guiot J. 1992. The combination of historical documents and biological data in the reconstruction of climate variations in space and time. In: B. Frenzel, C. Pfister and B. Gläser (Eds.), European Climate Reconstructed from Documentary Data. Methods and Results. Gustav Fischer Verlag, Stuttgart, Jena, New York: 93–104.

Hejnowicz Z., 1967. Zarys fizjologii sosny zwyczajnej (in Polish). Państwowe Wydawnictwo Naukowe, Warszawa–Poznań: 222 pp.

Helama S., Lindholm M., Timonen M. and Eronem M., 2004. Detection of climate signal in dendrochronological data analysis: a comparison of tree-ring standardization methods. Theoretical and Applied Climatology **79**: 239–254.

Hess M., 1968. Klimat terytorium miasta Krakowa (in Polish). Folia Geographica, series geographica-physica **1**: 35–97.

Hess M., 1974. Klimat aglomeracji krakowskiej (in Polish). Zeszyty Naukowe AGH, Sozologia i Sozotechnika **1** (361): 79–91.

Heussner K. U., 1996. Zum Stand der Dendrochronologie im unteren Odergebiet. In: S. Moździoch (Ed.), Człowiek a środowisko w środkowym i dolnym Nadodrzu. PAN, Instytut Archeologii i Etnologii, Spotkania Bytomskie, Wrocław **2**: 207–211.

Hollstein E., 1980. Mitteleuropäische Eichenchronologie. Trierer Grabungen und Forschungen. Mainz a. Rhein Trierer Grabungen **11**: 1–273.

Holmes R.S., 1994. Dendrochronology Program Library. Users Manual. University of Arizona, Tuscon: 51.

Holst J. Ch., 1993. Baukonjunkturen. In: R. Hammel-Kiesow (Ed.), Wege zur Erforschung städtischer Häuser und Höfe, Karl Wachholtz Verlag, Neumünster: 196–207.

Huber B., 1943. Über die Sicherheit jahrringchronologischer Datierung. Holz Roh- und Werkstoff **6**: 263–268.

Huber B., 1970. Dendrochronologie. Handbuch der Mikroskopie in der Technik 5, B. 1. Umschau Verlag, Frankfurt: 171–211.

Hurni J. P. and Orcel Ch., 1996. Dendrochronological results on buildings in Switzerland: geographical aspects. In: J. S. Dean, D. M. Meko and T. Swetnam (Eds.), Tree Rings, Environment and Humanity. Radiocarbon, Tucson: 533–542.

Inglod S., 1968. Zjawiska klimatyczno-meteorologiczne na Śląsku od XVI do połowy XIX wieku (in Polish). In: B. Świętochowski (Ed.), Z badań nad wpływem posuchy na rolnictwo na Dolnym Śląsku. Państwowe Wydawnictwo Naukowe, Wrocław: 9–29.

Jasnowska J., 1977. Czynniki wpływające na rozmiary słojów rocznych drewna sosny na torfowisku wysokim w zespole *Vacciniouliginosi-Pinetum* (in Polish). Rocznik Dendrologiczny **30**: 5–32.

Jaworski A. and Zarzycki K., 1983. Ekologia (in Polish). In: S. Białobok (Ed.), Jodła pospolita *Abies alba* Mill. Państwowe Wydawnictwo Naukowe, Warszawa: 317–430.

Jones P. D., Briffa K. R. and Schweingruber F. H. 1995. Tree-ring evidence of the widespread effects of explosive volcanic eruptions. Geophysical Research Letters **22**: 1333–1336.

Kaczka R. J., 2004. Dendrochronologiczny zapis zmian klimatu Tatr od schyłku małej epoki lodowej (na przykładzie Doliny Gąsienicowej) (in Polish). Prace Geograficzne **197**: 90–113.

Kalela-Brundin M., 1999. Climatic information from tree-rings of *Pinus sylvestris* L. and a reconstruction of summer temperatures back to AD 1500 in Femundsmarka, eastern Norway, using partial least squares regression (PLS) analysis. The Holocene **9** (1): 59–77.

Keller T. H., 1978. Einfluss niedriger $SO_2$ – Konzentrationen auf die $CO_2$ Aufnahme von Fichte und Tanne. Photosynthetica **12**: 316–322.

Kobayashi O., Funada R., Yasue K. and Ohtani J., 1998. Evaluation of the effects of climatic and non-climatic factors on the radial growth of Yezo spruce (*Picea jezoensiss Carr*) by dendrochronological methods. Annales des Sciences Forestières **55**: 277–286.

Kolchin B. A., 1962. Dendrokhronologia Novogroda (in Russian). Sovetskaya Arkhheologia **1**: 113–139.

Kolchin B. A. and Bitvinskas T. T., 1972. Sovremennye problemy dendrokhronologii. Problemy absolutnogo datirovania w arkheologii (in Russian). Izdatel'stvo Nauka, Moskva: 80–92.

Kornecki M., 1999. Kościoły drewniane w Małopolsce (in Polish). Kraków: 115 pp.

Kotarba A., 1994. Zapis Małej Epoki Lodowej w osadach jeziornych Morskiego Oka w Tatrach Wysokich (in Polish). Studia Geomorphologica Carpatho-Balcanica **27–28**: 61–69.

Koziarz A. and Koziarz M., 2007. Ocena stanu degradacji drzewostanów na przykładzie analizy dendroekologicznej w okolicy Trzebini (in Polish). Unpublished M.Sc. thesis, Wydział Geologii, Geofizyki i Ochrony Środowiska AGH, Kraków: 70 ms. pp.

Kożuchowski K. and Marciniak K., 1991. Współczesne zmiany kontynentalizmu klimatu w Polsce (in Polish). Acta Universitatis Nicolai Copernici **23** (76): 23–40.

Krause C., 1992. Ganzbaumanalyse von Eiche, Buche, Kieler und Fichte mit dendroökologischen Methoden. Dissertation, Universität Hamburg: 1–163.

Krawczyk A. and Krąpiec M., 1995. Dendrochronologiczna baza danych (in Polish). In: II Krajowa Konferencja: Komputerowe wspomaganie badań naukowych. Wrocław: 247–252.

Krąpiec M., 1996. Subfossil oak chronology (474 BC – 1529 AD) from Southern Poland. In: J. S. Dean, D. M. Meko and T. W. Swetnam (Eds.), Tree rings, Environment and Humanity. Radiocarbon: 813–819.

Krąpiec M., 1998. Oak Dendrochronology of the Neoholocene in Poland. Folia Quarternaria **69**: 5–133.

Krąpiec M., 2001. Holocene dendrochronological standards for subfossil oaks from the area of Southern Poland. Studia Quaternaria **18**: 47–63.

Krąpiec M., Łapo J. M. and Szychowska-Krąpiec E., 2006. Dendrochronologiczne datowanie wybranych zabytków architektury na Mazurach (in Polish). Studia Angerburgica **11**: 139–154.

Krąpiec M. and Szychowska-Krąpiec E., 2001. Tree-ring estimation of the effect of industrial pollution on pine (*Pinus sylvestris*) and fir (*Abies alba*) in the Ojców National Park (Southern Poland). Nature Conservation **58**: 33–42.

Krąpiec M. and Szychowska-Krąpiec E., 2003. Wpływ antropopresji na drzewostany Ojcowskiego Parku Narodowego w świetle analizy dendrochronologicznej (in Polish). In: J. Lach (Ed.), Dynamika zmian środowiska geograficznego pod wpływem antropopresji. Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, Akademia Pedagogiczna, Kraków: 200–210.

Krąpiec M., Szychowska-Krąpiec E. and Zielski A., 2005. Nowe standardy dendrochronologiczne z północno-wschodniej Polski a ustalanie miejsca pochodzenia drewna historycznego (in Polish). Prace Komisji Paleogeografii Czwartorzędu PAU **3**:117–125.

Krąpiec M., Szychowska-Krąpiec E., Danek M. and Kłusek M., 2006. Analiza dendrochronologiczna drewna pozyskanego w trakcie badań wykopaliskowych prowadzonych w Krakowie na Rynku Głównym po zachodniej stronie Sukiennic (in Polish). Materiały Archeologiczne **36**: 181–187.

KRZYSIK F., 1974. Nauka o drewnie (in Polish). Państwowe Wydawnictwo Naukowe, Warszawa: 900 pp.

KYNCL J. and *Kyncl* T., 1996. Dating of historical fir (*Abies alba*) wood in Bohemia and Morawia. Dendrochronologia **14**: 237–240.

KYNCL J. and KYNCL T., 1998. Standardchronologien der Nadelgehölze. Zeitgemäβiger Zustand in Böhmen und Mähren. Kolloquium „Probleme der mitteleuropäischen Dendrochronologie", Mikulčice, unpublished report: 1–4.

LADURIE E. LE ROY, 1972. Times of feast, times of famine: Beschämen history of climate since the year 1000. George Allen & Unwin Ltd., London: 428 pp.

LAMB H. H., 1980. Weather and climate patterns of the Little Ice Age. In: H. OESCHGER, O. MESSERLI and M. SVILAR (Eds.), Das Klima, Analysen und Modelle, Geschichte und Zukunft. Springer-Verlag, Berlin, Heidelberg, New York: 149–169.

LAMB H. H., 1984. Climate in the last thousand years: Natural climatic fluctuations and change. In: H. FLOHN and R. FANTECHI (Eds.), The Climate of Europe: Past, Present and Future. Reidel Publishing Company, Dordrecht, Boston, Lancaster: 25–64.

LECH E., 2006. Ocena stanu środowiska w Magurskim Parku Narodowym na podstawie monitoringu dendrochronologicznego drzewostanów (in Polish). Unpublished M.Sc. thesis, Wydział Geologii, Geofizyki i Ochrony Środowiska AGH, Kraków: 80 ms. pp.

LIEBERT S., GRABNER M. and WIMMER R., 1998. Beschämen 1000-year fűr chronology for East-Austria. European Dendrochronology Workshop "Eurodendro-98" – Dendrochronology and Environmental Trends, Kaunas: 18–23.

LIMANÓWKA D., 2001. Rekonstrukcja warunków klimatycznych Krakowa w pierwszej połowie XVI wieku (in Polish). Materiały Badawcze, seria Meteorologia **33**: 95–136.

LINDHOLM M., ERONEN M., TIMONEN M. and MERILÄINEN J., 1999. A ring-width chronology of Scots pine from northern Lapland covering the last two millennia. Annales Botanicae Fennici **36**: 119–126.

LINDHOLM, M., MERILÄINEN, J. and ERONEN, M., 2000. A 1,250-year ring-width chronology of Scots pine for south-eastern Finland, the southern part of the boreal forest belt. Dendrochronologia 1998–1999 16–17: 185–192.

LUTERBACHER J., DIETRICH D., XOPLAKI E., GROSJEAN M. and WANNER H., 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science **303**: 1499–1503.

LUTERBACHER J., KOENIG S. J., FRANKE J., VAN DER SCHRIER G., ZORITA E., MOBERG A., JACOBEIT J., DELLA-MARTA P. M., KÜTTEL M., XOPLAKI E., WHEELER D., RUTISHAUSER T., STÖSSEL M., WANNER H., BRÁZDIL R., DOBROVOLNÝ P., CAMUFFO D., BERTOLIN C., VAN ENGELEN A., GONZALEZ-ROUCO F. J., WILSON R., PFISTER C., LIMANÓWKA D., NORDLI Ø., LEIJONHUFVUD L., SÖDERBERG J., ALLAN R., BARRIENDOS M., RÜDIGER GLASER, RIEMANN D., HAO Z. and ZEREFOS C. S., 2010a. Circulation dynamics and its influence on European and Mediterranean January-April climate over the past half millennium: results and insights from instrumental data, documentary evidence and coupled climate models. Climate Change, Springer Science+Business Media: 1–35.

LUTERBACHER J., XOPLAKI E., KÜTTEL M., ZORITA E., GONZÁLEZ-ROUCO J. F., JONES P. D., STÖSSEL M., RUTISHAUSER T., WANNER H., WIBIG J. and PRZYBYLAK R., 2010b. Climate Change in Poland in the Past Centuries and its Relationship to Europe Climate: Evidence from Reconstructions and Coupled Climate Models. In: R. PRZYBYLAK (Ed.), The Polish Climate in the Context: An Historical Overview. Springer Science+ Business Media: 4–39.

LÜHRTE A. VON, 1992. Dendroecological studies on pine and oak in the forests of Berlin (West). Lundqua Report **34** (2–3): 79–89.

MÁCOVÁ M., 2008, Dendroclimatological comparison of native *Pinus sylvestris* and invasive *Pinus strobus* in different habitats in the Czech Republic. Preslia **80**: 277–289.

MALEWICZ M. H., 1980. Zjawiska przyrodnicze w relacjach dziejopisarzy polskiego średniowiecza (in Polish). Monografie z dziejów nauki i techniki **123**: 49–57.

MARUSZCZAK H., 1994. Process of food products in Polish territory as index of climatic oscillations in the Little Ice Age. Geographia Polonica **63**: 119–127.

Maruszczak H., 1999. Zmiany środowiska w okresie historycznym (in Polish). In: L. Starkel (Ed.), Geografia Polski – środowisko przyrodnicze. Wydawnictwo Naukowe PWN, Warszawa: 180–221.

Meko D. M., 1985. Temporal and spatial variation of drought in Marocco. Proceedings from Drought, Water Management and Food Production, 1985 Nov. 21, Agadir, Marocco: 55–82.

Mirowski R., 2005. Kościoły drewniane. Najbardziej polskie… (in Polish). Krajowy Ośrodek Badań Dokumentacji i Zabytków, Warszawa: 204 pp.

Mroczko T. and Arszyński M., 1995. Architektura gotycka w Polsce (in Polish). Instytut Sztuki PAN, Warszawa: 603 pp.

Muter E., 2004. Dynamika przyrostu na grubość i jej uwarunkowania u wybranych gatunków drzew w Puszczy Niepołomickiej (in Polish). Unpublished Ph.D. thesis, Akademia Rolnicza, Kraków: 88 ms. pp.

Müller-Stoll H., 1951. Vergleichende Untersuchungen über die Abhängigkeit der Jahrringfolge von Holzart, Standort und Klima. Bibliotheca Botanica **122**: 1–93.

Naurzbaev M. M. and Vaganov E. A., 2000. Variation of early summer and annual temperature in east Taymir and Putoran (Siberia) over the last two millennia inferred from tree rings. Journal of Geophysical Research **105**: 7317–7326.

Niedźwiedź T., 1981. Sytuacje synoptyczne i ich wpływ na zróżnicowanie przestrzenne wybranych elementów klimatu w dorzeczu górnej Wisły (in Polish). Rozprawy habilitacyjne UJ **58**: 1–165.

Niedźwiedź T., 2004. Rekonstrukcja warunków termicznych lata w Tatrach od 1550 roku (in Polish). Prace Geograficzne **197**: 57–88.

Niedźwiedź T., 2010. Summer temperatures In the Tatra Mountains During the Maunder Minimum (1645–1715). In: R. Przybylak (Ed.), The Polish Climate In the European Context: An Historical Overview. Springer Netherlands: 397–406.

Nocoń P., 2000. Późnogotycki piec kaflowy z zamku w Chudowie koło Gliwic (in Polish). Alma Mater UJ, special issue: 122–126.

Oleksyn J., Fritts H. C. and Hughes M. K., 1993. Tree-ring analyses of different *Pinus sylvestris* provenances, *Quercus robur*, *Larix decidua* and *L. decidua* × *L. kaempferi* affected by air pollution. Arboretum Kórnickie **38**: 87–111.

Park W. K. and Yadav R. R., 1998. Reconstruction of May Precipitation (AD 1731-1995) in West-Central Korea from Tree Rings of Korea Red Pine. Journal of Korean Meteorological Society **34**: 459–465.

Pfister C., Schwarz-Zaneti G. and Wegmann M., 1996. Winter severity in Europe: The fourteenth century. Climatic Change **34**: 91–108.

Piotrowicz K., 2003. Warunki termiczne zim w Krakowie w latach 1792–2002 (in Polish). Folia Geographica, series geographica-physica **33–34**: 67–88.

Piotrowicz K., 2007. Temperatura powietrza (in Polish). In: D. Matuszko (Ed.), Klimat Krakowa w XX wieku. Instytut Geografii i Gospodarki Przestrzennej UJ, Kraków: 99–111.

Podlaski R., 2002. Radial growth trends of fir (*Abies alba* Mill.), beech (*Fagus sylvatica* L.) and pine (*Pinus sylvestris* L.) in the Świętokrzyski National Park (Poland). Journal of Forest Science **48** (9): 377–387.

Porter S. C., 1986. Pattern and forcing of Northern Hemisphere glacier variations during the last millenium. Quaternary Research **26**: 27–48.

Przybylak R., 2008. Zmiany klimatu Polski i Europy w ostatnich stuleciach (in Polish). Kosmos, Problemy Nauk Biologicznych **57** (3–4): 195–208.

Przybylak R., Wójcik G. and Marciniak K., 2004. Zmienność warunków termiczno-opadowych w Polsce w okresie 1501–1840 w świetle danych historycznych (in Polish). Przegląd Geograficzny **76**: 5–28.

Przybylak R., Majorowicz J., Wójcik G., Zielski A., Chorążyczewski W., Marciniak K., Nowosad W., Oliński P. and Syta K., 2005. Temperature changes in Poland from the $16^{th}$ to the $20^{th}$ centuries. International Journal of Climatology **25**: 73–791.

Przybylski T., 1972. Variability of Scots Pine (*Pinus silvestris* L.) of Polish provenances. Arboretum Kórnickie **17**: 121–167.

PUCHALSKI T. and PRUSINKIEWICZ Z., 1975. Ekologiczne podstawy siedliskoznawstwa leśnego (in Polish). Państwowe Wydawnictwo Rolnicze i Leśne, Warszawa: 362 pp.

PUKIENE R. and BITVINSKAS T., 2001. Long-term climate change and vegetation dynamics in bogs. Eurodendro 2001, Davos 2001: 240–241.

SCHICHLER B., LEVANIČ T., ČUFAR K. and ECKSTEIN D., 1997. Climate-growth relationship of fir in the Dinaric Mountains in Slovenia using different standardizations and response function calculations. Dendrochronologia **15**: 207–214.

SCHULTHESS J., 1990. Der Einfluss von Entwässerung auf die Bewaldung eines Hochmoors. Diplomarbeit, Geographischer Institut Universität Zürich: 1–190.

SCHWEINGRUBER F. H., 1985. Dendrochronological zones in the coniferous forests of Europe. Dendrochronologia **3**: 67–75.

SCHWEINGRUBER F. H., 1993. Trees and Wood in Dendrochronology. Springer-Verlag, Berlin: 402 pp.

SCHWEINGRUBER F. H., 1996. Tree Rings and Environment, Dendroecology. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf: 602 pp.

SHIYATOV S. G., 1995. Reconstruction of climate and the upper timberline dynamics since AD 745 by tree-ring data in the polar Ural Mountains. In: P. HEIKINHEIMO (Ed.), Proceedings, International Conference on Past, Present and Future Climate: Publications of the Academy of Sciences of Finland: 6.

SHOVE D. J., 1987. Sunspot cycles and weather history. In: M. R. RAMPINO (Ed.), Climate. History, Periodicity and Predictability. Van Nostrand Reinhold, New York: 355–377.

SPURK M., 1997. Dendroklimatologische Untersuchungen an Kiefern (*Pinus sylvestris* L.) der planarkollinen Stufe in Deutschland. Dendrochronologia **15**: 51–72.

STAHLE D. W. and CLEAVELAND M. K., 1994. Tree ring reconstructed rainfall over the southeastern U.S.A. during the medieval warm period and little ice age. Climatic Change **26**: 199–212.

STAHLE D., W., CLEAVELAND M. K., HAYNES G. A., KLIMOWICZ J., MUSHOVE P., NGWENYA P. and NICHOLSON S. E., 1997. Development of a rainfall sensitive tree-ring chronology in Zimbabwe. The 8th Symposium on Global Change Studies, 1997 Feb., Long Beach Ca. American Mateorological Society, Boston: 205–211.

STĘPIEŃ-SAŁEK M., 2004. Magurski Park Narodowy (in Polish). Przyroda Polska **2**: 16–17.

SZYCHOWSKA-KRĄPIEC E., 1997a. Dendrochronological pine scale (1662–1996 AD) for the Małopolska area (south Poland). Bulletin of the Polish Academy of Sciences, Earth Sciences **45**: 1–13.

SZYCHOWSKA-KRĄPIEC E., 1997b. Ocena wpływu zanieczyszczeń przemysłowych na drzewostany sosnowe Puszczy Niepołomickiej i Borów Nowotarskich w świetle analizy dendrochronologicznej (in Polish). Zeszyty Naukowe AGH, Geologia **23** (4): 389–406.

SZYCHOWSKA-KRĄPIEC E., 2000. Późnoholoceński standard dendrochronologiczny dla jodły *Abies alba* Mill. z obszaru południowej Polski (in Polish). Kwartalnik AGH, Geologia **26** (2): 17–299.

SZYCHOWSKA-KRĄPIEC E., 2003a. Przykład wykorzystania analizy dendrochronologicznej w datowaniu obudów górniczych w Kopalni Soli w Bochni (in Polish). Sylwan **147** (9): 47–52.

SZYCHOWSKA-KRĄPIEC E., 2003b. Application of Dendrochronological Analysis in Dating of Timbers from the Wieliczka Salt Mine. Biuletyn PAN, seria Nauk o Ziemi **51** (2): 99–118.

SZYCHOWSKA-KRĄPIEC E., 2007. Dendrochronological studies of wood from mediaeval mines of polymetallic ores in Lower Silesia (SW Poland). Geochronometria **26**: 61–68.

SZYCHOWSKA-KRĄPIEC E. and KRĄPIEC M., 2005. The Scots Pine Chronology (1582–2004 AD) for the Suwałki Region, NE Poland. Geochronometria **24**: 41–51.

SZYCHOWSKA-KRĄPIEC E. and KRĄPIEC M., 2006. Regional pine chronology (*Pinus sylvestris* L.) from NE Poland. In: 7th International Conference on Dendrochronology, Cultural Diversity, Environmental Variability, June 11–17 Beijing, China: 128.

SZYCHOWSKA-KRĄPIEC E. and WIŚNIOWSKI Z., 1996. Zastosowanie analizy przyrostów rocznych sosny zwyczajnej (*Pinus silvestris*) do oceny wpływu zanieczyszczeń przemysłowych na przykładzie Zakładów Chemicznych „Police" (woj. szczecińskie) (in Polish). Zeszyty Naukowe AGH, Geologia **22** (3): 281–299.

TIMONEN M., MIELIKAINEN K. and HELAMA S., 2006. Climate from the 7520-year unbroken Scott pine tree-ring chronology for Finnish Lapland. In: 7th International Conference on Dendrochronology, Cultural Diversity, and Environmental Variability, June 11–17, Beijing, China: 132.

Tomanek J., 1997. Botanika leśna (in Polish). Państwowe Wydawnictwo Rolnicze i Leśne, Warszawa: 506 pp.

Touchan R., Meko D. M. and Hughes M. K., 1999. A 396-year reconstruction of precipitation in Southern Jordan. Journal of the American Water Resources Association **35**: 45–59.

Vaganov E. A., Hughes M. K. and Shashkin A. V, 2006. Growth Dynamics of Conifer Tree Rings. Images of Past and Future Environments. Springer-Verlag, Berlin–Heidelberg: 341 pp.

Villalba R., Boninsegna J. A., Lara A., Veblen T. T., Roig F. A., Aravena J. C. and Ripalta A., 1996. Interdecadal climatic variations in millennian temperature reconstructions from southern South America. In: P. D. Jones, R. S. Bradley and J. Jouzel (Eds.), Climatic variations and forcing mechanisms of the last 2000 years. Springer-Verlag, Berlin: 161–192.

Wachter A., 1979. Untersuchungen zum Weisstannensterben in Baden-Württemberg. Allgemeine Forst und Jagd-Zeitschrift **150**: 196–203.

Ważny T., 1990. Aufbau und Anwendung der Dendrochronologie für Eichenholz in Polen. Dissert. Univ. Hamburg: 213 pp.

Wertz B., 2009. Dendrochronologiczna ocean wpływu imisji przemysłowych na przyrost radialny głównych gatunków drzew iglastych z Wyżyny Kieleckiej (in Polish). Unpublished Ph.D. thesis, Uniwersytet Rolniczy, Kraków: 124 ms. pp.

Wilczyński S., 1999. Dendroklimatologia sosny zwyczajnej (*Pinus sylvestris* L.) z wybranych stanowisk w Polsce (in Polish). Unpublished Ph.D. thesis, Zakład Klimatologii Leśnej Akademii Rolniczej w Krakowie: 84 ms. pp.

Wilczyński S., 2005. Regiony dendroklimatyczne sosny zwyczajnej (*Pinus sylvestris* L.) w Karpatach polskich. Acta Agraria et Silvestria, series Silvestris **43**: 43–51.

Wilczyński S., 2006. The variation of tree-ring widths of Scott pine (*Pinus sylvestris* L.) affected by air pollution. European Journal of Forest Research **125**: 213–219.

Wilczyński S., Krąpiec M., Szychowska-Krąpiec E. and Zielski A., 2001. Regiony dendroklimatyczne sosny zwyczajnej w Polsce (in Polish). Sylwan **8**: 53–61.

Wilczyński S. and Skrzyszewski J., 2002a. The climatic signal in tree-rings of Scots pine (*Pinus sylvestris* L.) from foot-hills of Sudetic Mountains (southern Poland). Forstwissenschaftliches Zentralblatt **121**: 15–24.

Wilczyński S. and Skrzyszewski J., 2002b. Dependence of Scots pine tree-ring on climate conditions in southern Poland (Carpatian Mts.). Electronic Jurnal of Polish Agricultural Universities (Forestry) **5** (2): 9.

Wilczyński S. and Skrzyszewski J. 2003. Dendrochronology of Scots pine (*Pinus sylvestris* L.) in the Mountains of Poland. Journal of Forest Science **49** (3): 95–105.

Wilson R. J. S., Luckman B. H. and Esper J., 2005. A 500 year dendroclimatic reconstruction of spring-summer precipitation from the Lower Bavarian Forest region, Germany. International Journal of Climatology **25**: 611–630.

Witanowski M. R., 2001. Dawny powiat chęciński (in Polish). Regionalny Ośrodek Studiów i Ochrony Środowiska Kulturowego. Kielce: 499 pp.

Wnęk K., 1999. Dzieje klimatu Galicji w latach 1848–1913 (in Polish). Historia Iagellonica, Kraków: 9–173.

Wodzicki T. J. and Zajączkowski S., 1983. Variation of seasonal cambial activity and xylem differentiation in a selected population of *Pinus silvestris* L. Folia Forestalia Polonica, Ser. A **25**: 5–23.

Woś A., 1999. Klimat Polski (in Polish). Wydawnictwo Naukowe PWN, Warszawa: 302 pp.

Yadav R. R., Park W. K. and Bhattacharyya A., 1999. Spring-temperature variations in western Himalaya, India as reconstructed from tree-rings: AD 1390–1987. The Holocene **9**: 85–90.

Zaitz E., 2006. Sprawozdanie z badań archeologicznych prowadzonych w Krakowie w 2003 i 2004 przy przebudowie nawierzchni płyty Rynku Głównego po zachodniej stronie Sukiennic (in Polish). Materiały Archeologiczne **36**: 79–143.

Ząbecki W. and Wierus J., 1993. Rozmiar uszkodzenia iglastych drzewostanów przez imisje przemysłowe w Ojcowskim Parku (in Polish). Prace Muzeum Szafera Prądnik **7–8**: 133–141.

Zhu H. F., Fang X., Q., Shao X., M. and Yin Z. Y., 2009. Tree-ring based February-April temperature reconstruction for Changbai Mountain in Northeast China and its implication for East Asian monsoon. Climate of the Past **5**: 661–666.

ZIELSKI A., 1992. Dendrochronological studies on pine growing under the influence of air pollution near the Pulp and Paper Factory in Kwidzyn, Poland. In: T. S. BARTHOLIN, B. E. BERGLUND, D. ECKSTEIN and F. H. SCHWEINGRUBER (Eds.), Tree Rings and Environment, Lundqua Report **34**: 360–363.

ZIELSKI A., 1997. Uwarunkowania środowiskowe przyrostów radialnych sosny zwyczajnej (*Pinus sylvestris* L.) w Polsce północnej na podstawie wielowiekowej chronologii (in Polish). Wydawnictwo UMK, Toruń: 1–127.

ZIELSKI A. and KRĄPIEC M., 2004. Dendrochronologia (in Polish). Wydawnictwo Naukowe PWN, Warszawa: 1–328.

ZINKIEWICZ W., 1946. Badania nad wartością przyrostu rocznego drzew dla studiów nad wahaniami klimatycznymi (in Polish). Annales Universitatis Mariae Curie-Skłodowska **6**: 178–228.

STRESZCZENIE

# WIELOWIEKOWE CHRONOLOGIE SOSNY (*Pinus sylvestris* L.) I JODŁY (*Abies alba* Mill.) Z REGIONU MAŁOPOLSKI ORAZ ICH INTERPRETACJA PALEOKLIMATYCZNA

W pracy przedstawiono wyniki badań dotyczących dendrochronologii i denroklimatologii sosny zwyczajnej (*Pinus sylvestris* L.) i jodły pospolitej (*Abies alba* Mill.) z obszaru Małopolski. Wynikiem tych badań było zestawienie dwóch 900-letnich regionalnych standardów obejmujących następujące okresy czasu: 1109–2004 AD dla jodły i 1091–2006 AD dla sosny. Analizą objęto około 3000 prób drewna, które pochodziło z wykopalisk archeologicznych, obiektów architektonicznych, wyrobisk górniczych kopalni soli w Wieliczce i Bochni, a także z drzew rosnących.

W trakcie prac nad konstrukcją standardów uzyskano datowania bezwzględne licznych obiektów. Datowania te wskazywały lub potwierdzały czas ich budowy, przebudowy czy napraw. Wśród tych obiektów były liczne zabytkowe kościoły z województwa małopolskiego i świętokrzyskiego. Dzięki przeprowadzonym badaniom uzyskano daty wznoszenia konstrukcji dachowych kościołów w Czerwonym Chotlu (1449 AD), Zborówku (1458 AD), Chrobrzu (1547 AD), Krzcięcicach (1538 AD), Strzelcach Wielkich (1784 AD), Grabiach (1736 AD), czy kościele kolegiackim w Wiślicy (1355 AD). Datowania dendrochronologiczne pozwoliły też określić daty przeprowadzania remontów konstrukcji dachowych w kościołach w Szańcu (1657 AD), Kossowie (1776 AD), Małogoszczy (1658 AD), Dobrowodzie (1762 AD), Nowym Korczynie (1776 AD), Jędrzejowie (1827 AD), Górce Kościelnickiej (1689 AD) i Wiślicy (1443 AD). Poza datowaniami obiektów architektonicznych zestawione standardy umożliwiły datowanie bezwzględne artefaktów pochodzących z wykopalisk archeologicznych, np. zabudowań drewnianych na Rynku w Krakowie, po zachodniej stronie Sukiennic. Pozostałości podwalin dawnych budynków o konstrukcjach szkieletowych czy fragmenty ruchomych stoisk, straganów, elementy studni i rur wodociągowych pochodzą z końca XIII i połowy XIV w. Jednymi z najstarszych badanych elementów drewnianych pochodzących z wykopalisk archeologicznych okazała się studnia zlokalizowana niedaleko Krakowa w Zakrzowcu, która została wykonana w latach 30–40. XIII w. Inne obiekty drewniane wydatowane dendrochronologicznie, a pochodzące z wykopalisk archeologicznych prowadzonych na Rynku w Bytomiu, Starym Mieście w Rybniku, czy na Starym Mieście w Wodzisławiu Śląskim są młodsze. Dzięki przeprowadzonym badaniom określono czas ich wznoszenia, przebudowy, a także rozbudowy. Stare kramy na Rynku w Bytomiu, a także nawierzchnia Rynku zostały wybudowane w końcu XIII w. Młodsze są konstrukcje budynków mieszkalnych na Rynku w Rybniku pochodzące z połowy XVI w. (1555 AD). W Wodzisławiu Śląskim zabudowa Starego Miasta i fragmenty drogi reprezentują szeroki przedział czasu: od 1658 r. aż do początków XIX w. (1816 AD).

Wiele datowań dendrochronologicznych uzyskano dla drewna występującego w kopalniach soli w Bochni i Wieliczce. Te zabytkowe kopalnie powstałe w XIII w. na starych poziomach eksploatowanych w średniowieczu zawierają drewno z tamtych czasów, które zachowane jest w wyrobiskach górniczych jako elementy obudowy, bądź jako urządzenia i sprzęt górniczy. Przeprowadzone analizy dendrochronologiczne drewna z obu kopalń pozwalają nie tylko określić czas ścinania drzew, których drewno użyto do budowy obudów czy urządzeń, ale także określić czas ich przebudów czy napraw. Najstarsze drewno w obudowach górniczych stwierdzono w komorze Dusząca (1387, 1390, 1405, 1422 AD) i szybie Goryszowski (1485–1495 AD) w kopalni soli w Wieliczce. Komora Dusząca jest przykładem wyrobiska, gdzie mamy drewno pochodzące z różnego czasu, świadczące o naprawach obudowy około 1422 roku, 1480, 1630, 1692, 1817 i 1905 r. W wielu przypadkach datowanie dendrochronologiczne drewna występującego w wyrobiskach jest zgodne z czasem ich powstawania, jak na przykład komory Stanetti w kopalni soli w Bochni (1824–1858 AD) czy podsadzka w koszu Rabsztyn

(1721, 1728, 1738 i 1740 AD). Datowanie dendrochronologiczne uzyskały również zabytkowe narzędzia i urządzenia górnicze, np. kierat Ważyński w kopalni w Bochni (1673, 1702 AD).

Przedstawione przykłady datowania materiału badawczego różnego pochodzenia świadczą o szerokich możliwościach zastosowania nowo utworzonych standardów w datowaniach różnych obiektów: począwszy od obiektów architektonicznych, poprzez wyrobiska górnicze, aż po artefakty występujące w wykopaliskach archeologicznych.

Utworzone chronologie regionalne dla Małopolski wykazują wysoką zbieżność z chronologiami regionalnymi z obszarów sąsiednich. Małopolski standard jodłowy najwyższe podobieństwo wykazał z chronologią austriacką (*t* = 20.079) i niemiecką zestawioną dla Saksonii i Turyngii (*t* = 19.928), nieco niższe natomiast ze wzorcem przyrostowym z południa Niemiec (*t* = 18.568) i Czech (*t* = 17.348). Niższe wartości podobieństwa uzyskała Małopolska chronologia sosnowa, *t* około 12, ze standardem kujawsko-pomorskim i środkowoniemieckim, *t* = 10.789. Z pozostałymi porównywanymi standardami chronologia małopolska uzyskała niższe wartości *t* w granicach 6: standardy północnopolski, warmińsko-mazurski, suwalski, gotlandzki.

Chronologie małopolskie są nie tylko precyzyjnym narzędziem datującym, ale także naturalnym archiwum klimatycznym mającym zastosowanie w rekonstrukcji klimatu w przeszłości. Ekstremalne zdarzenia pogodowe, takie jak: mroźne, długotrwałe zimy, gorące i suche lata, późne przymrozki czy powodzie identyfikowane są jako lata wskaźnikowe. W czasie ostatnich 900 lat w chronologii jodłowej wyróżniono 120 lat wskaźnikowych pozytywnych i negatywnych, z przewagą lat negatywnych. Najwięcej lat wskaźnikowych wystąpiło w XIII w. (21). Znacznie mniej zidentyfikowano lat wskaźnikowych w chronologii sosnowej, tylko 57; aż 12 z nich wystąpiło w XVI w. W relacjach przyrost roczny – klimat funkcja odpowiedzi wykazała zdecydowany wpływ temperatury miesięcy zimowych, w przypadku jodły całego okresu zimowego: od grudnia do marca, natomiast u sosny najważniejszą rolę odgrywa koniec okresu zimy (luty, marzec). Opady u obu gatunków miały mniejsze znaczenie W ostatnich dziesięcioleciach w przyrostach rocznych jodeł i sosen obserwuje się redukcje szerokości ich przyrostów. Są one wywołane w głównej mierze wpływami zanieczyszczeń przemysłowych powietrza. Zanieczyszczenia te powodują zmiany w zależnościach przyrost roczny – klimat. U sosny wpływ na szerokość słojów obok temperatury lutego i marca ma również temperatura grudnia. Natomiast u jodły obok temperatur miesięcy zimowych (XII–III) dodatkowo pojawia się wpływ temperatury lipca i sierpnia. W przypadku opadów w okresie wzmożonego oddziaływania zanieczyszczeń przemysłowych nie obserwuje się ich znaczącego wpływu i nie odgrywają one większej roli.

Zależność przyrostu rocznego od średnich miesięcznych temperatur 4 miesięcy zimowych (XII, I, II, III) u jodły i dwóch (II, III) u sosny została wykorzystana do rekonstrukcji tych temperatur w ostatnich 900 latach w Małopolsce. Obie nowo zestawione chronologie małopolskie zostały wykorzystane jako predyktor. Na ich podstawie wyznaczono okresy występowania niskich temperatur w całym okresie zimy (chronologia jodłowa) i pod koniec okresu zimowego (chronologia sosnowa). Niskie temperatury w całym okresie zimowym wystąpiły w latach: 1200–1320, 1350–1450, 1490–1530, 1560–1595, 1630–1780, 1820–1920, natomiast chłodne okresy końca zim (II–III) zidentyfikowano w latach: 1140–1190, 1220–1320, 1365–1405, 1570–1780, 1830–1920 i 1959–1990. Niektóre z wymienionych okresów chłodnych korelują się z okresami mniejszej aktywności Słońca. Minimum Wolfa zaznaczające się na przełomie XIII i XIV w. (1280–1350) powiązać można z zaznaczającym się epizodem chłodnych miesięcy zimowych XII–III u jodły i II–III u sosny w 1280–1320 w długotrwałym, ponad stuletnim okresie ochłodzenia 1200–1320. Chłodny okres zaznaczający się na przełomie XV i XVI w. (1490–1530) skorelować można z minimum Spörera (1460–1550), a 150-letni okres chłodnych zim w XVII i XVIII w. (1630–1780) z minimum Maundera (1645–1715).

Przeprowadzone rekonstrukcje temperatur zimowych w Małopolsce i wyznaczone na ich podstawie fazy cieplejszych i chłodniejszych zim znajdują odzwierciedlenie w schemacie długookresowych zmian klimatycznych: Średniowiecznym Okresie Ciepła, Małej Epoce Lodowej i Współczesnym Okresie Ocieplenia. Okresy występowania wyższych temperatur (XII–III) w 1130–1200 w przypadku jodły i (II–III) w 1100–1140 w przypadku sosny można powiązać z końcową fazą Średniowiecznego Okresu Ciepła. Natomiast długotrwały okres występowania niekorzystnych temperatur zim rozpoczynający się około 1560/1570 r. interpretować można jako początek Małej Epoki Lodowej, której zakończenie na obszarze Małopolski przypada na lata 20. XX w. Ostatni z wyróżnionych długookresowych zmian klimatu, Współczesny Okres Ocieplenia, zaznacza się w przeprowadzonych rekonstrukcjach w trzeciej dekadzie ubiegłego wieku.

Wyniki analiz dendrochronologicznych drewna sosnowego i jodłowego z Małopolski i opracowanie 900-letnich standardów regionalnych w znaczący sposób uzupełnia zestaw polskich standardów dendrochronologicznych. Zestawione chronologie dla Małopolski są drugimi w Polsce, tak długimi wzorcami przyrostowymi dla drewna tych gatunków (po chronologii północnopolskiej dla sosny autorstwa A. Zielskiego i południowopolskiej chronologii jodłowej opracowanej przez autorkę).