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Optical density of Scots pine wood and climatic conditions in Toruń, Poland

Aleksandra Pospieszyńska* [a], **Marcin Koprowski** [b], **Rajmund Przybylak** [c]

Nicolaus Copernicus University in Toruń, Poland

* **Correspondence:** Department of Meteorology and Climatology, Nicolaus Copernicus University in Toruń, Poland. E-mail: opos@umk.pl

[a] https://orcid.org/0000-0003-2532-7168, [b] https://orcid.org/0000-0002-0583-4165, [c] https://orcid.org/0000-0003-4101-6116

Abstract. The aim of the studies was to evaluate the usefulness of the microscopic features of wood in characterising the climatic conditions of a period for which only proxy data are available. Samples were taken from historical wood from Koronowo collegiate church and from a living Scots pine tree growing in the Toruń-Wrzosy site. All measurements were performed using ImageJ software. The dendroclimatological analysis was carried out in the program DendroClim2002. The results show a correlation between the microscopic features of wood and climatic conditions. For the period 1951–2000 the maximum optical density of pine wood depends on average May air temperature and June precipitation, with correlation coefficients of -0.32 and -0.29, respectively. A similar correlation was found for mean maximum and minimum temperatures in May; -0.35 and -0.37, respectively. Additional correlations between selected meteorological elements and the maximum optical density of the wood were found using 30-year moving averages and moving intervals.

Key words:
dendroclimatology,
Pinus sylvestris L.,
optical density of wood,
MXD

Introduction

In the conditions of the Polish Lowland, Scots Pine responds to air temperature as winter turns to spring, and to rainfall in the vegetative period. This research complements analyses carried out for the Kuyavian-Pomeranian region on the basis of annual growth rings for the period 1173–2000 for Scots pine wood (*Pinus sylvestris* L.) (Zielski 1997; Wójcik et al. 2000; Koprowski et al. 2012). Climatic conditions indisputably affect the incremental pattern of trees in a given climatic zone and the amount of early and late wood produced. Therefore, these conditions also affect the internal structure of the wood and its density. The abovementioned relationships were of interest e.g. Pumijumnong and Park (1999), Decoux et al. (2005), Alexandersson (2009), Fonti et al. (2010).

The basic research problem is to find and describe the relationship between the microscopic features of wood and climatic conditions. Determining such dependencies could improve or confirm the accuracy of current reconstructions of average air temperatures from January to April. This relates not only to the thermal regimes outside these months, but also to other meteorological elements (including atmospheric precipitation, insolation, etc.).

Study area

The research area is located in a transitional temperate climate zone. It has a high variability of weather types from day to day and quite a varied course of meteorological elements from year to year (Wójcik and Marciniak 2006). The high variability of meteorological conditions is reflected in tree-ring patterns. Until now, reconstructions based on microscopic features have mainly been carried out on trees growing in the upper forest border (*e.g.* Dolgova and Solomina 2010).

Both sites are located in northern part of Poland (Fig. 1). In terms of regional climates proposed by Okołowicz and Martyn (2004), Toruń lies in the Nadwiślański Region in a temperate warm zone of year-round precipitation. The area is subject to Atlantic, Baltic and continental influences. The Nadwiślański region characterized by warm summer and a moderately cool winter with low precipitation.

According to the geobotanical classification of Matuszkiewicz (1993) the Koronowo and Toruń-Wrzosy dendrochronological sites are located in the single land E1.6.b. (Chełmińsko-Dobrzyńska land, Nadwiślański Włocławsko-Bydgoski district). In terms of natural forest regionalization (Trampler et al. 1990), both dendrochronological sites are also located in a single land, III Wielkopolska-Pomorska, with Toruń-Wrzosy in the district of Toruń-Płockie Kotlina, and Koronowo in the district of Pojezierze Krajeńskie. The area is dominated by fresh and dry habitats with an unfavourable environment – low soil trophic levels and low precipitation.

Fig. 1. Map with location of research sites

The site in Toruń-Wrzosy is of mixed fresh coniferous forest changing to fresh coniferous forest (Wrzosy Forestry, branch 115). Podzols on loose sands dominate (Błaszkowski 2002). The area around Koronowo from which the historical dendrochronological material originates has a predominance of coniferous forest habitats created on outwash sand podzolic soils.

Methods and materials

The dendrochronological material was collected from two sites – historical and growing wood of Scots pine (*Pinus sylvestris* L). The material taken from historical wood (increment cores) coming from a pine ceiling beam in the collegiate church of the Assumption of the Blessed Virgin Mary in Koronowo. The sample was dated at 1601–1676 (Marciniak 2008; Koprowski et al. 2012).

The material from the living tree (a slice) came from a Scots pine from Toruń Wrzosy Forest District to the north of Toruń. The sample extracted at a height of 6 m (Błaszkowski 2002). The sample was selected based on the availability of material and its parameters (including its sensitivity being close to the mean for the chronology). According to dendrochronological methodology, samples should be taken at breast height (~1.3 m). However, for samples taken from historical timber it is not possible to clearly determine the height from which a given sample would have originated. Thus it can be assumed that the selection of a sample from a height of 6 m is burdened with the same error as the historical timber from Koronowo. The material used in the microscopic analysis is the same as that used to create the KUJAWPOM chronology (Zielski et al. 2010). Specific samples were selected based on correlation values, response functions and mean sensitivity so that they would best represent the characteristics of the entire chronology.

This research can be considered as complementing Scots pine tree-ring analyses for the Kujawsko-Pomorskie region for the period 1173–2000 (Koprowski et al. 2012). In the conditions of the Polish Lowlands, Scots pine responds to the air temperature as winter turns to spring, and to rainfall during the growing season (mainly the summer).

The dendrochronological method is based on the assumption that in our climate trees produce one growth ring each growing season. At the beginning of the growing season the trees usually produce a wide, pale belt of earlywood. The tracheids have thin cell walls and cell lumens are wide. At the end of the growing season, latewood is produced. In Scots pine this layer is thinner and darker. The tracheids have thick cell walls and a small cell lumen. Earlywood has the function of conducting water and nutrients, while latewood plays a more mechanical role. Thus, during the growing season, the optical density of wood varies from low to higher values, reaching the maximum at the end of the growing season. The occurrence of unfavorable climatic conditions (low temperatures, low or no precipitation) causes a reduction in tracheid light and an increase in the thickness of cell walls, and hence an increase in the density of wood.

Cell lumen (CAL) and cell wall (CAW) dimensions are characteristic for different parts of growth rings (Fig. 2). A decrease in CAL indicates either an increase in CAW, provided no change in thickness of cell wall, or a decrease in CAT, or a change in both. Independent CAW growth or a decrease in CAT indicates the appearance of transition latewood. A synchronous increase in CAW and decrease in CAT indicates that true latewood is being created. The CAL curve, plotted cell by cell for the entire ring, should decrease at a steeper angle for true latewood.

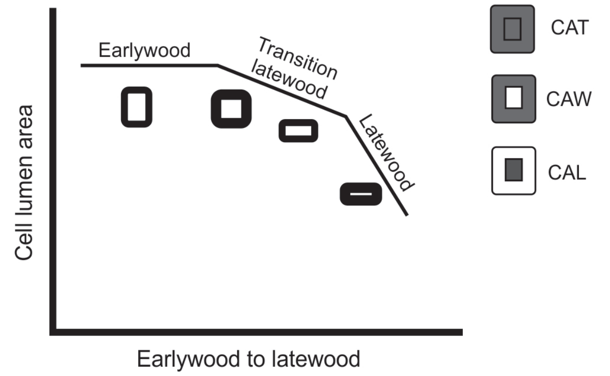

Fig. 2. A exemplar curve of vessel lumen along a tree ring, showing the relationship between vessel lumen and earlywood, transition latewood and latewood. Shading in the key indicates: total cell surface (CAT), cell wall area (CAW) and cell lumen (CAL) (own elaboration after Cook and Kairiukstis 1990)

The first part of the hypothetical curve (Fig. 2), which is horizontal, represents true earlywood, where the shape and thickness of the cell wall does not change. The transition to latewood is characterised by a change in the shape of the cell or the thickness of the cell wall, but not both, and is represented by the next slope of the curve. The last part of the curve shows true latewood, where both the shape and thickness of the walls have been changed, and the line angle is steeper. The shapes of actual CAL curves (obtained by measurement) should be compared against this hypothetical curve.

One of the ways to illustrate the anatomical features of wood is by using tracheoidograms. These are curves showing changes in the cell-size of wood over the growing season. Radial tracheid size, cell wall thickness and cell lumen are measured along the radius and their values are assigned to a specific cell. Initially, the radial size of the tracheid is large and the cell walls are thin. As the transitional zone begins to form, the radial size of the cells steadily decreases, and the thickness of the cell wall rises to a certain limit, to then decrease again in the last cells of the ring edge.

The measurements of tree-ring width and the actual chronology were made using CooRecorder and CDendro (www.cybis.se) software. The chronology was standardised and indexed using CRONOL and ARSTAN software. The homogeneity of the growth-ring sequence was analysed in the COFECHA program (Grissino-Mayer 2001). This software made it possible to construct actual, standard and residual chronology for the analyzed sites. The basic characteristics used to describe the chronology were: average width of growth ring, standard deviation, mean sensitivity (S), autocorrelation, correlation (r), and the value of t (Student's t-test).

The next stage was the laboratory preparation of dendrochronological material. In order to remove organic substances, the sample was boiled in distilled water for about 1 hour. The sampled material was divided into smaller parts of length approximately 1.0–1.5 cm. The samples were prepared using a microtome (Fig. 3A) to take 20-µm-thick sections (Fig. 3D). In order to reveal structures in the wood, the microscopic sections were stained with Safranin T (Fig. 3B) and embedded in glycerin gelatin (Fig. 3C). Next, photos were taken under the microscope

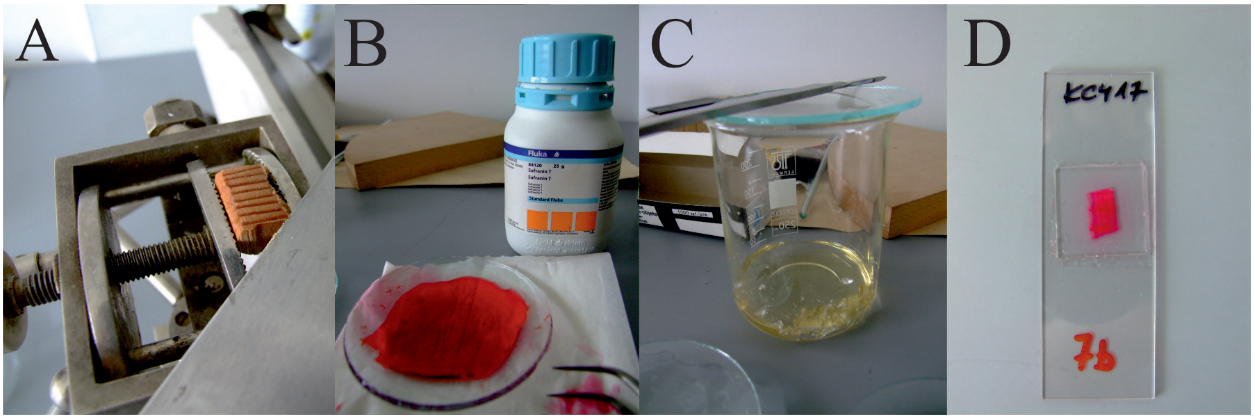

Fig. 3. Successive stages of laboratory preparation (see text for description)

using a Canon 30D camera (55 mm focal length, 5/0.15 ocular lens).

A series of photos was taken for each section (Fig. 4), and these were then combined into a single image using Adobe Photoshop CS3 software These combined images were further processed in the same software (including adjustment of contrast and brightness). Then, colour desaturation was carried out.

Twenty repeat measurements per growth ring were made along the radial and tangential cross-section). All measurements were made using ImageJ software, and their results were presented as a measurement series for each particular parameter.

Measurements were of: number of cells (earlywood and latewood), cell lumen length, cell lumen width, cell width and cell wall thickness (Fig. 5). Decoux et al. (2004), also Gärtner (2009) pointed out the possibility of using cell parameters to indirectly determine density:

Cell length: $C_l = L_l + w_1 + w_2$

Cell lumen: $L_a = L_l \cdot L_w$

Cell area: $C_a = Cl \cdot (Lw+2w_a) = Cl \cdot Cw$

Cell wall: $W = 2w_a \cdot (Cl+Cw) - (2w_a)^2$ (Decoux et al. 2004)

Cell-wall proportion: $W_p = W/C_a$

Density (g/cm³): $D = W_p \cdot 1.5$ (Gärtner 2009).

Key: *L_a – cell lumen; C_a – cell area; W – cell wall; *Cl – cell length; Cw – cell width; *Ll – lumen length *Lw – lumen width; * – measured values.

The dendroclimatological analysis was performed in DendroClim2002 software (Biondi and Waikul 2004), which allowed the microscopic features of the wood to be correlated with specific meteorological elements. Standard tests and statistical methods used in dendrochronology were used for the series of microscopic features. Based on the series of density (D – see equation above) the maximum wood density (MXD) and minimum wood density (MND) values were selected and used for further analysis. Pointer years were determined by the method proposed by Vogel and Schweingruber (2001) using WEISER software.

The climatological data was comprised of series of average monthly air temperatures (calculated based on their mean daily as well as daily maximum and minimum values) and monthly sums of atmospheric precipitation for the Toruń-Wrzosy site in the period 1951–2000 (Przybylak et al. 2012; Pospieszyńska and Przybylak 2018).

The analysis of the response function describes the relationship between the growth and meteorological conditions of a given season (use of mean values and monthly sums). The analysis takes into account the basic meteorological factors for plant growth (mainly air temperature and atmospheric precipitation). However, this method does not allow to detect the impact of short-term extreme weather conditions. It is based on the multiple regression method. To determine additional relationships between selected meteorological elements and the maximum optical density of wood, shorter periods were used, i.e. 30-year moving averages. Additionally, moving intervals were used to identify shorter periods within the calibration period 1951–

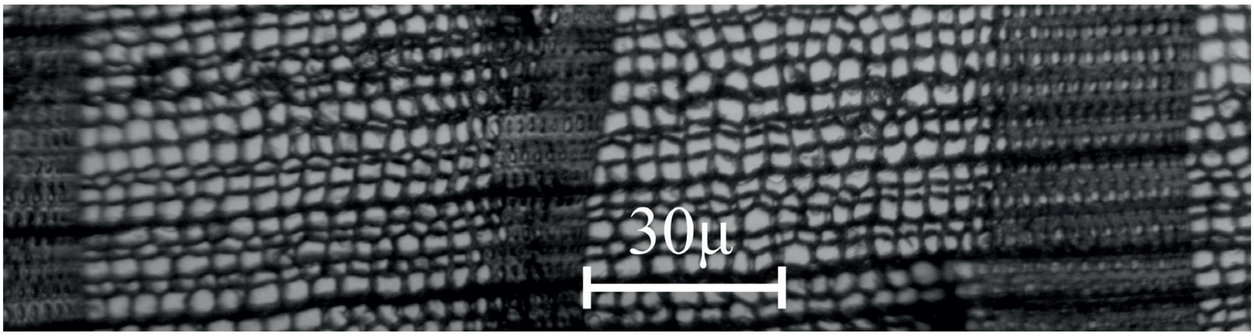

Fig. 4. Example of analysed panoramic image of a sample

2000 (Biondi and Waikul 2004). In addition to the correlation coefficient being determined, so too was the coefficient of the response function, which describes the climate–growth relationship; in this case, the climate–MXD relationship specifically.

Results and discussion

Residual chronology of the Toruń area

The residual chronology for the optical density of wood was created based on material from two periods: 1601–1676 (Fig. 6) and 1951–2000 (Fig. 7).

The actual chronology for the Koronowo site covered the years 1601–1671. The average ring width was above 1.60 mm, with 1.17 mm for earlywood, and 0.43 mm for latewood. The standard deviation of the chronology was 0.899. The standard chronology had an autocorrelation of 0.900 and mean sensitivity of 0.190.

From year to year, the average optical density of wood in the period 1601–1676 was from 0.726 to 1.218 g/cm^3, with an average of 0.930 (Fig. 6). MXD

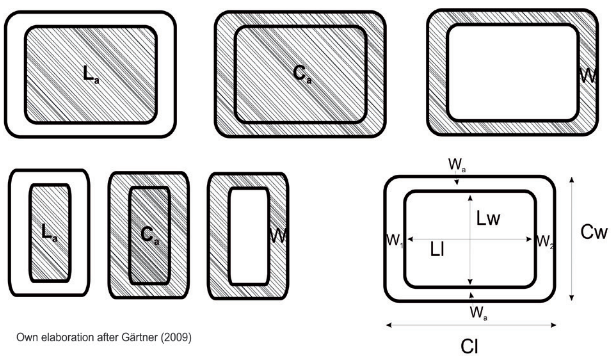

Fig 5. Analysed cell parameters according by Gaertner 2009 (see text for description)

averaged around 1.500 g/cm^3, with a maximum above 2.000 g/cm^3. On average, MND was below 0.500 g/cm^3 and was similar to that observed in the second period – 1951–2000 (Fig. 7).

The actual chronology for the Toruń site covered 79 years (1921–2000). The analysis period was shortened to 1951–2000. This is because in the first 30-year part of the 79-year period the lack of data with which to apply a 30-year average had a clear impact, despite the use of indexation, so it was decided to omit reporting results for those years, and only to use their data in the calculation of 30-year rolling means for the years 1951 onwards. The trees on the site had healthy and well-formed crowns. The average ring width was 1.6 mm over the period considered. The standard deviation of the chronology was 1.33. The standard chronology had an autocorrelation of 0.940 and mean sensitivity of 0.197. From year to year, the average optical density of wood in the period 1951–2000 was from 0.560 to 0.960 g/cm^3, with an average of 0.710. MXD averaged approximately 1.200 g/cm^3, with a maximum of 1.720 g/cm^3.

The dendroclimatological analysis for the 17th century can be verified from weather information in historical sources (diary, letters, chronicles, etc.). Where the chronology coincides with the period of instrumental meteorological measurements, a standard calibration and verification procedure is carried out. The calibration period was set as 1951–2000.

For this period, the maximum optical density of Scots pine wood from trees in Toruń shows climate dependency with regard to May temperatures and June precipitation, with r=-0.32 and -0.29, respectively, and statistically significant at the 0.05 level. These dependencies confirm the important

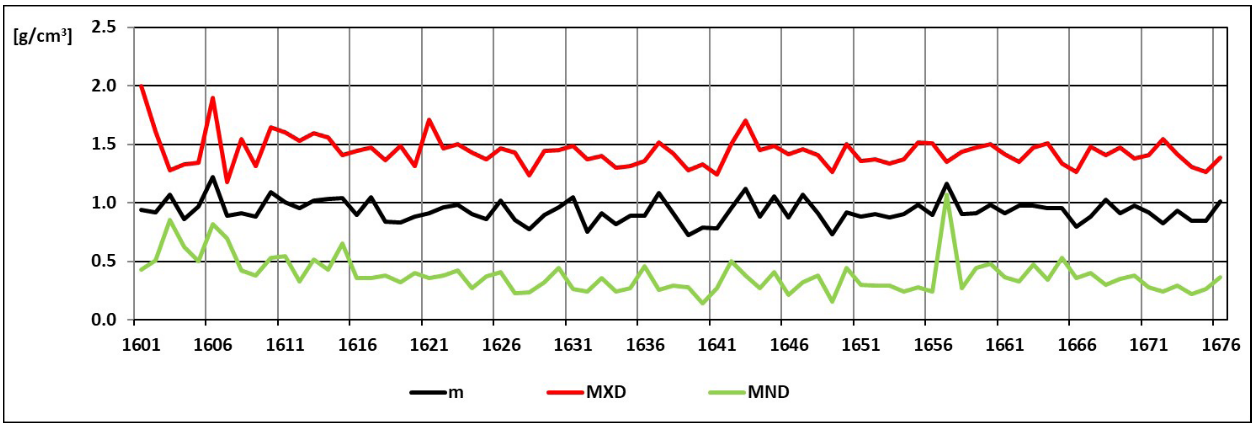

Fig. 6. Course of optical density (g/cm³) of Scots pine in Koronowo in the period 1601–1676 (m – average, MXD – maximum optical density of wood, MND – minimal optical density of wood)

role of May thermal activity in tree growth. May has very dynamic changes in air temperature, with prolonged cold periods, and frosts unfavourable to plant growth. This is due to the relatively frequent inflow of Arctic air masses to the Toruń region (Przybylak et al. 2012). Stronger correlations were also found for average maximum and minimum temperatures. Dependencies on both were confirmed for May, with r=-0.35 and -0.37, respectively.

The average temperature if August of the previous year in the period 1953–1994 had a correlation of -0.46 with MXD (Fig. 8). The response function limited the potential calibration period to the years 1953–1991. In this period the relationship between air temperature and MXD was strongest. The other correlations proved to be insufficiently strong.

The atmospheric precipitation for October of the previous year had a correlation of 0.33 in eight 30-year periods within the 1963–2000 period, from 1963–1992 to 1971–2000 (Fig. 9). The correlation coefficient of precipitation for September of the current season was 0.31 for the period 1951–1985. The use of moving intervals confirmed a correlation with precipitation in October of the previous year at 0.33 in the sub-periods 1965–1972 and 1993–2000.

The response function limited the potential calibration period for October of the previous year to the years 1966–2000. During this period the relationship of precipitation to MXD was the strongest. As with average air temperature, the other correlations proved to be insufficiently strong.

The average maximum air temperature (Fig. 10) in August of the previous year influenced MXD values (r=-0.47, 1953–1993), as did the temperatures for October of the current year (r=0.36, 1952–1995). The response function verified the correlations for October and August. One important relationship is that of the maximum August air temperature in the period 1952–1990.

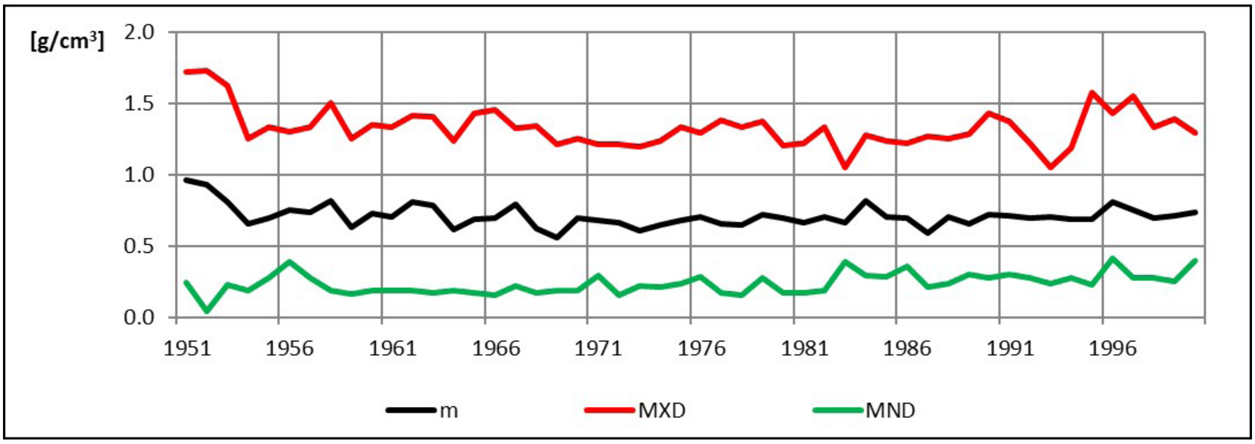

Fig. 7. Course of optical density (g/cm³) of Scots pine in Toruń in the period 1601–1676 (key as in Fig. 5)

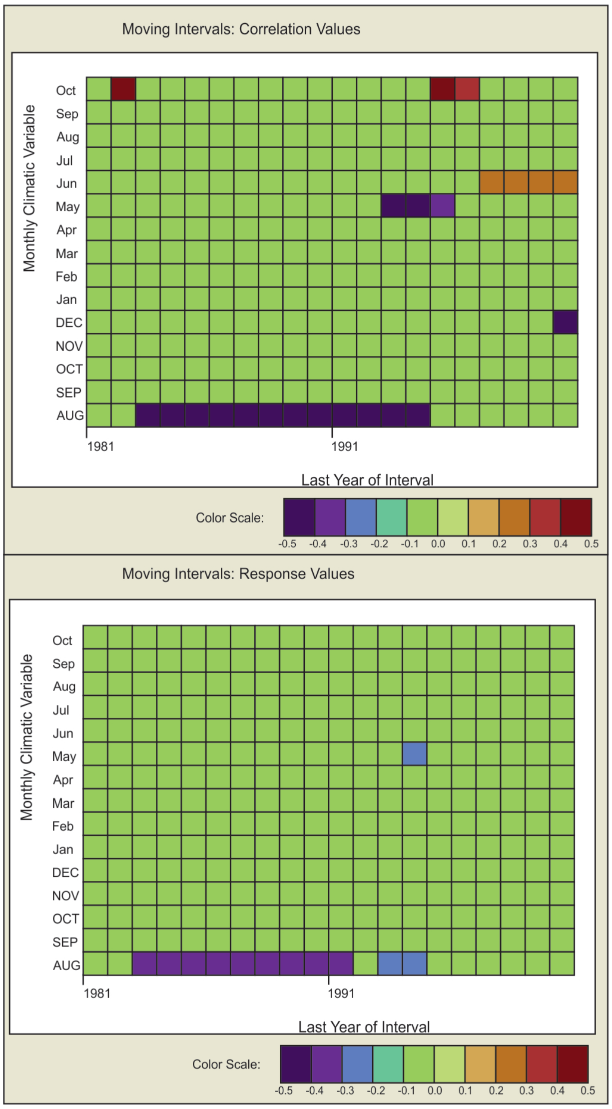

Fig. 8. 30-yr moving average of correlation coefficient (upper figure) and response function coefficient (lower figure) between average monthly air temperature and MXD of residual chronology at the Toruń-Wrzosy site in the period 1951–2000. Correlation coefficient and response function values marked on the x-axis for 1981, 1982, etc. indicate values for the 30-yr period 1951–1980, 1952–1981, etc.

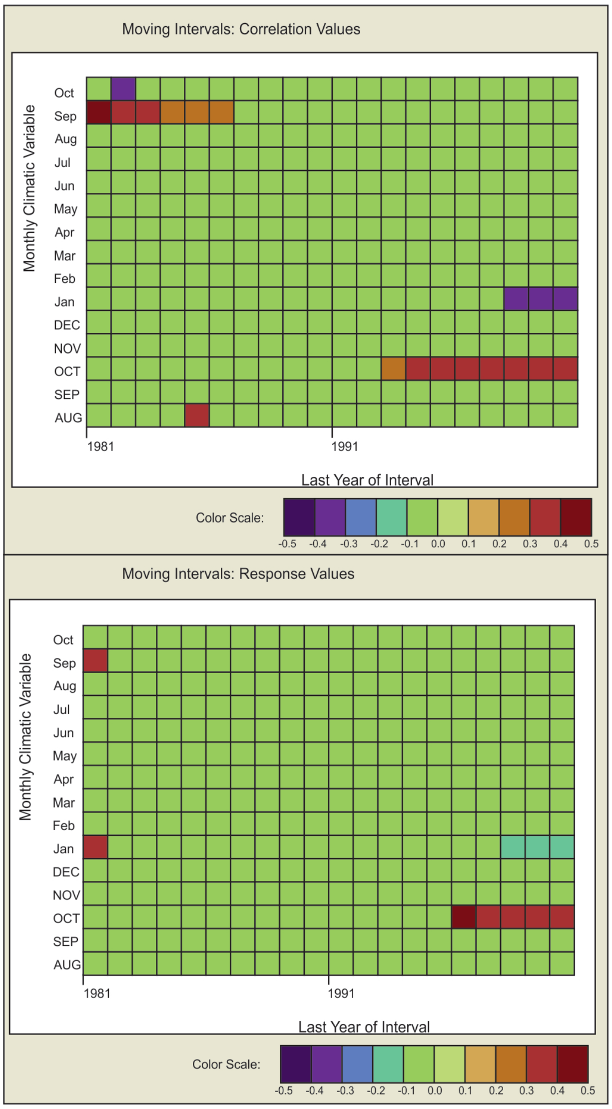

Fig. 9. 30-yr moving average of correlation coefficient (upper figure) and response function coefficient (lower figure) between total monthly precipitation and MXD of residual chronology at the Toruń-Wrzosy site in the period 1951–2000. Key as in Fig. 7

Meanwhile, the average minimum air temperature (Fig. 11) in August of the previous year for 1954–1994 and October of the previous year for 1966–2000 influenced the values of MXD (r =-0.48 and r=0.49, respectively). This last period was confirmed by the response function. The minimum temperature in May of the current year for 1963–1997 and July of the current year for 1953–1992 also affected MXD (r=-0.48 and 0.31, respectively). A significant dependence was determined for May.

Similar analyses have been carried out for trees from the upper limit of their occurrence; Dolgova and Solomina (2010) reconstructed summer temperature using the MXD values of pine in the Caucasus. Correlation coefficients of average temperature and MXD for individual summer months ranged from 0.34 to 0.63. Weaker correlations were determined for atmospheric precipitation. The limiting influence of air temperature was clearly indicated in this case. For the Toruń region, both air temperature and atmospheric precipitation are limiting factors. Similar limiting factors were indicated by, *inter alia*, Pumijumnong and Park (1999). Cell surface, diameter and density of teak

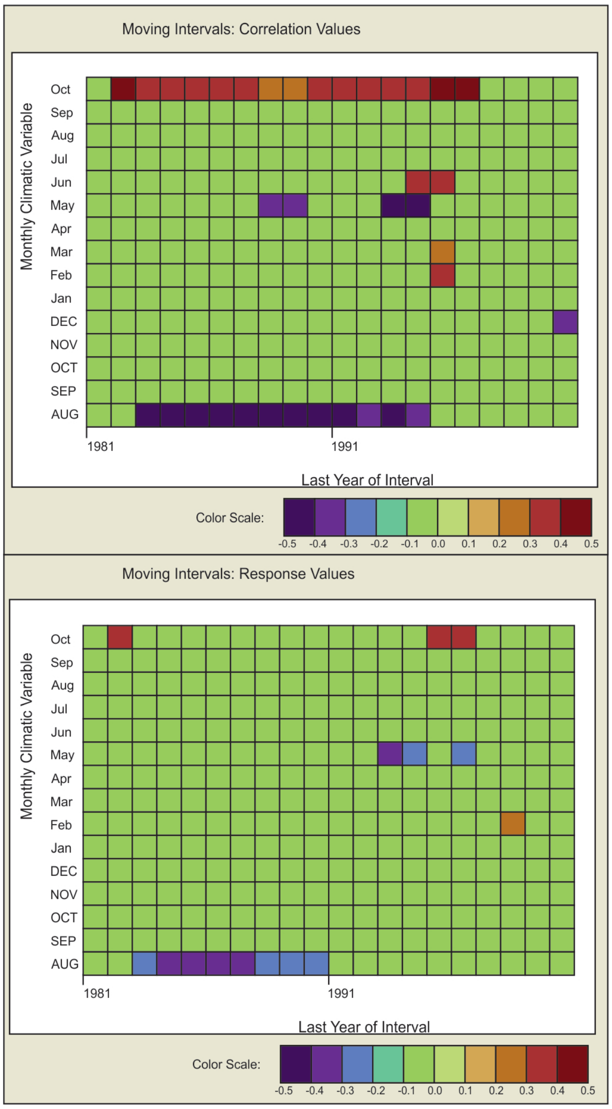

Fig. 10. 30-yr moving average of correlation coefficient (upper figure) and response function coefficient (lower figure) between average monthly maximum air temperature and MXD of residual chronology at the Toruń-Wrzosy site in the period 1951–2000. Key as in Fig. 7

wood served to describe the thermal and rainfall conditions of Southeast Asia. The dependence of wood density on precipitation was correlated with May precipitaiton (r=-0.39) and April and May temperatures (r≈-0.30). The results for the Toruń region have similar correlations.

Pointer years for microscopic wood characteristics

Pointer years are defined as years in which the majority of individuals display the same growth tendency (Zielski and Krąpiec 2004). They attest to the existence of an external factor contributing either to a reduction in ring width in relation to the previous year (a negative pointer year), or to an increase in ring width over the previous year (a positive pointer year). As predicted, negative pointer years should be characterised by an increase in optical wood density resulting from trees' response to stress factors (e.g. low spring temperatures, lack of summer precipitation). Similarly, in positive indicator years, the optical density of wood should be lower.

In the period 1601–1676 there were 13 pointer years: 8 positive and 5 negative (Table 1). Certain positive years had a lower density than the long-term mean, which can be explained by assuming larger vessel lumens and thinner cell walls. For 8 pointer years, there was an increase in optical density (5 positive pointer years and 3 negative). In the case of the negative years, the increase in density is justified, but in the case of positive years, the increase in density may be the result of unfavourable growing conditions during a certain portion of the growing season.

Table 1. Growth-ring pointer years and optical density of wood in residual chronology, Koronowo site (positive – red, negative – blue, maximum density values – grey)

Year	Pointer years			Optical density [g/cm³]
	Total growth	Early wood	Late wood	
1601	Negative	-		0.941
1602	Positive	+	+	0.918
1603	Negative	-		1.066
1611	Positive	+		1.004
1616	Negative	-		0.900
1622	Positive	+		0.959
1624	Negative	-		0.907
1637	Negative			1.086
1645	Positive	+		1.054
1650	Positive			0.916
1651	Positive			0.883
1656	Positive	+	+	0.895
1660	Positive	+		0.981
1664	Positive			0.951
1668	Positive		+	1.025
1601–1676	x	x	x	0.930

In the period 1951–2000 there were 25 pointer years (9 positive and 16 negative – Table 2). Five extreme years were identified (with index values +/-3), the positive ones being 1967, 1980 and 1997 and the negative ones 1974 and 1976. However, the dependence of extreme wood density values on the occurrence of positive and negative indicator years in the tree-ring width chronology is not entirely unambiguous.

There was an unambiguous response to climatic conditions in 1997, when the maximum optical density was above the average for the total period. The probable cause was the very dry June and August. There was another unambiguous response in 1980, when the minimum optical density was below the average for the total period. The probable cause is unknown and must have been non-climatic.

February and March of 1967 were very warm (Przybylak et al. 2012), which is confirmed by the value of the minimum density of earlywood. In the case of 4 positive and 1 negative years, both high MXD values and low MND values were noted, which clearly indicates the combined effect of thermal and precipitation factors during the growing season. This makes it difficult to carry out a climate reconstruction.

In addition to the pointer years for tree-ring width, pointer years for optical wood density values were also determined (Fig. 12). Of the 38 pointer years common to both chronologies, only in 14 cases was there a concurrent change in both ring width and wood density (positive pointer years: 1962, 1963, 1964, 1966, 1991, 1995, 1997; negative: 1954, 1955, 1956, 1959, 1983, 1993, 2000). In the remaining cases, pointer years occurred in only one of the chronologies or the changes in a shared pointer year were not concurrent. This means that, in those cases, the influence of factors other than climate was recorded.

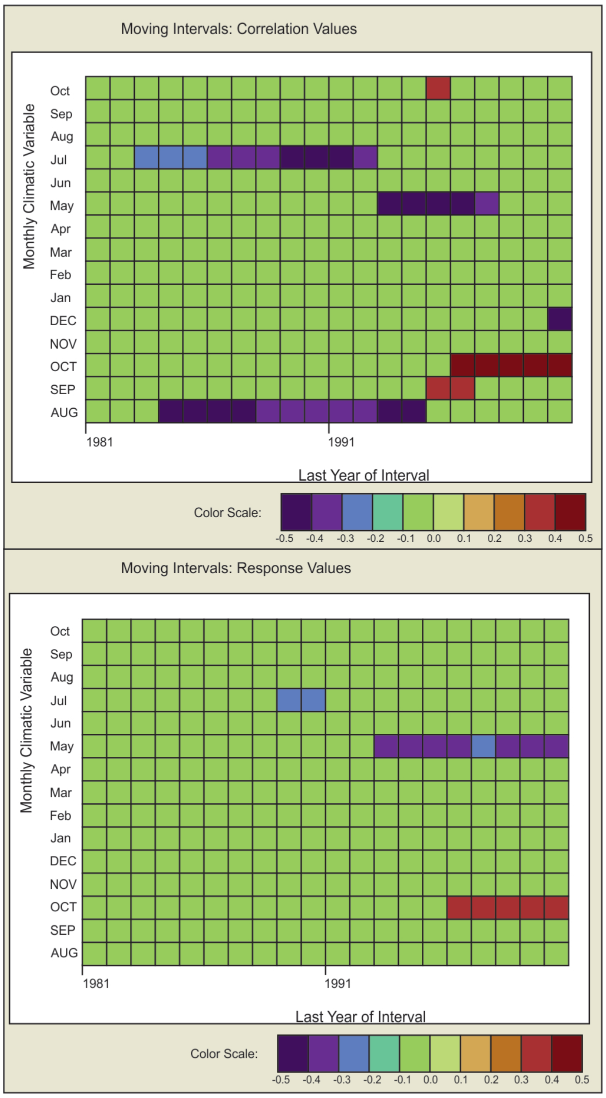

Fig. 11. 30-yr moving average of correlation coefficient (upper figure) and response function coefficient (lower figure) between average monthly minimum air temperature and MXD of residual chronology at the Toruń-Wrzosy site in the period 1951–2000. Key as in Fig. 7

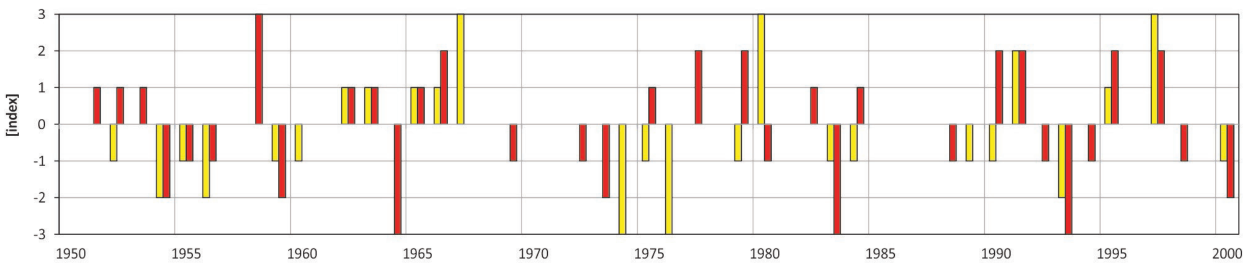

Fig. 12. Pointer years for the residual chronology of WRZ303 and residual chronology for the optical density of wood for the period 1951–2000 (yellow bars- RWI, red bars- MXD)

Table 2. Growth-ring pointer years and maximum latewood density (MXD) and minimum earlywood density (MND) of the residual chronology (positive – red, negative – blue; for densities of values in grey)

Year	Index	Early wood	Late wood	Optical density [g/cm³]	MXD	MND
1952	-1			0.93	1.73	0.04
1954	-2	-		0.65	1.25	0.19
1955	-1	-		0.70	1.33	0.27
1956	-2	-	-	0.75	1.30	0.39
1959	-1	-	-	0.63	1.25	0.16
1960	-1	-	-	0.72	1.35	0.19
1962	1	+		0.81	1.41	0.19
1963	1	+		0.78	1.41	0.17
1965	1			0.68	1.43	0.17
1966	1			0.70	1.46	0.16
1967	3	+	+	0.79	1.33	0.22
1974	-3	-		0.65	1.24	0.21
1975	-1		-	0.68	1.33	0.24
1976	-3	-	-	0.70	1.29	0.29
1979	-1		-	0.72	1.38	0.27
1980	3	+	+	0.70	1.21	0.17
1983	-1	-	-	0.66	1.05	0.39
1984	-1	-		0.81	1.28	0.29
1989	-1	-	-	0.66	1.29	0.30
1990	-1	-	+	0.72	1.43	0.27
1991	2	+		0.71	1.38	0.30
1993	-2	-		0.70	1.05	0.24
1995	1	+		0.69	1.58	0.23
1997	3	+	+	0.75	1.55	0.27
2000	-1	-	-	0.74	1.29	0.40
1951–2000	x	x	x	0.71	1.33	0.23

Summary

In the course of the research, comparison was made between the macro- and microscopic method and their usefulness in climate reconstruction. Despite the assumption that the microscopic method would allow for a higher resolution reconstruction, analysis showed a far lower correlation of wood structures to climatic conditions. The weak and ambiguous influence of thermal and precipitation conditions on the structure of wood made it impossible to carry out a climate reconstruction.

The results indicate that, compared to the traditional method, the microscopic method correlates less well with climate features. This indicates that the macroscopic method is more suitable for climate reconstructions. The microscopic method may be helpful in the reconstruction of the May thermal regime, but the results of this reconstruction will be uncertain and excessively burdened by large errors. The use of 30-year moving averages and moving intervals made it possible to indicate additional relations between air temperature and atmospheric precipitation on the one hand, and the maximum optical density of wood on the other; however, these relationships are not stable over time.

The research results show a correlation between microscopic wood features and climatic conditions. The historical timber from the Cistercian church in Koronowo dated to the turn of the 16th to 17th century exhibits an optical density of wood that in

pointer years is 0.02–0.16 g/cm^3 above the average (1601–1676).

Comparing pointer years and extreme years against measurement data for 1951–2000 confirmed the complex dependence of MXD on environmental conditions. The maximum optical density of wood for the Toruń-Wrzosy site in the period 1951–2000 showed the largest statistically significant negative correlation with May thermal conditions and June precipitation, with correlation coefficients of -0.32 and -0.29, respectively.

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