Trees (1991) 5: 75–82

Structure and Function
Trees

Influence of climatic factors upon tree rings of *Larix decidua* and *L. decidua* x *L. kaempferi* from Pulawy, Poland

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Received October 1990/Accepted February 8, 1991

Summary. Dendroclimatological techniques are used to assess the impact of climatic factors on tree-ring width of *Larix decidua* and *L. decidua* x *L. kaempferi* (= *L.* x *eurolepis*) growing in two experimental plots established in 1914 in south-west Poland. One plot included F_1 progeny grown from seeds of an artificial crossing between European and Japanese larch. The other plot included progeny from maternal trees of European larch. Total ring width, earlywood width and latewood widths were dated, standardized and related to monthly climatic data using response function and stepwise multiple regression analyses. Wide rings in larch are associated with high precipitation in May-July, cool conditions in July-September of the preceding year, and cool dry conditions in August. Ring widths in *L.* x *eurolepis* are more dependent upon precipitation than ring widths in *L. decidua.* Latewood widths in *L.* x *eurolepis* are more dependent on high temperatures in June and July than latewood in *L. decidua* as well as total width and earlywood measurements. Variations in latewood were relatively independent of variations in earlywood and total wood. The variability of ring widths in these larches was greater than the variability reported for larches in many alpine sites and for other conifer species in some regions of North America.

Key words: Dendrochronology – Larch – Latewood – Earlywood – Climatic factors

Introduction

There has been considerable interest for many years in using European and Japanese larch and their hybrids in tree improvement programs. These species have been recommended for reforestation, for fiber and energy. Although the ecological characteristics of *Larix* are relatively well known (for review, see: Schober 1949; Bialobok 1986), little information is available on the effects of climatic factors upon ring growth. Most tree-ring studies of larches have analyzed stands growing at the upper altitudinal forest limit (Serre 1978; Bednarz 1982; Holzhauser 1984; Adamenko 1986) or at the polar forest limit (Shijatov 1978).

Investigations of Michalak (1977a, b) indicated that leading shoot growth of *L. decidua* started in north-west Poland on April 29 and finished on September 9. The mean growing period for this species was 98 days. The growing season of other tree species was much shorter: Scots pine, 60 days; silver fir, 73 days; and Norway spruce, 63 days. The same tendency was observed for diameter growth of larch, which began in April-May and finished in September (Table 1).

The purpose of this study is to determine the statistical relationships between climatic factors and ring-width measurements from *L. decidua* and *L.* decidua x *L. kaempferi* trees from artificial crossing, growing in an experimental plot established in 1914 by S. Z. Kurdiani at Pulawy, Poland. Dendroecological techniques were used to relate the climatic factors to variations in earlywood, latewood and total ring width.

Table 1. The percent ring-width growth in different months for *Larix decidua*

Country	Month					
	A	M	J	J	A	S
Denmark[a]	–	19	31	33	16	1
Czechoslovakia[b]	6	33	33	16	11	1
USSR (1962)[c]	–	10	30	40	17	3
USSR (1963)[c]	–	17	57	17	7	2

[a] Ladefoged 1952
[b] Chalupa 1965
[c] Nadezdin 1971

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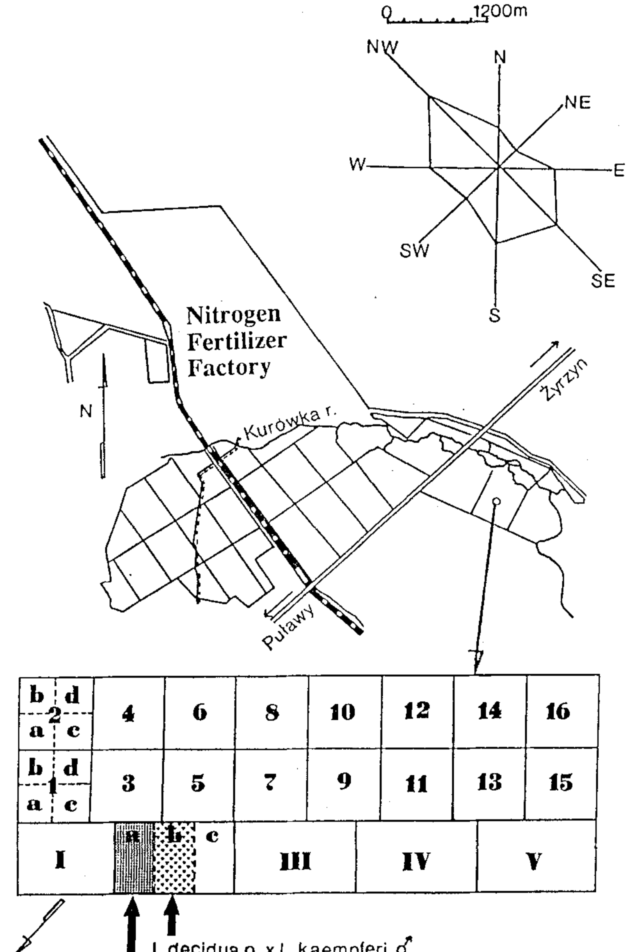


Fig. 1. Map of the Forest Range Ruda and plan of the experimental area as published by Kurdiani (1932). Plots 1–16 are different Scots pine populations. The prevailing wind directions for the region are shown in the upper right corner. *Plots a* and *b* are 13 × 35 m

Materials and methods

Description of the experimental area and plant material

The experimental area was planted with *L. decidua* and *L. decidua* x *L. kaempferi* (= *L.* x *eurolepis*) in 1914 by S. Z. Kurdiani in compartment 25 of the present experimental Forest Range Ruda at the Institute of Cultivation and Fertilization (IUNG), Pulawy, Poland (Fig. 1). This was the first artificial intraspecific crossing between European and Japanese larch. Somewhat earlier, in 1900, E. J. Elwes and A. Henry described a hybrid between *L. decidua* and *L. kaempferi*. However, this report concerned only observations made on a spontaneous hybrid in natural conditions (Wright 1976). More information about this experiment can be found in Oleksyn and Giertych (1984) and Oleksyn (1985).

The mean annual precipitation from 1920 to 1987 for that region was 570 mm, and the mean monthly temperature ranged from –3.76°C in January to 18.46°C in July. The experimental area lies at 51°37′N, 22°06′E, altitude 140 m, and it is slightly north-west sloping. The soils are sandy, composed of shallow sands and gravels (Tomaszewski 1928). Phytosociologically the area is a *Pineto-Quercetum* association (Matuszkiewicz and Matuszkiewicz 1956). The soil was well drained, shallow, sandy and low in nutrients, which are not optimal conditions for larch growth (Schober 1949).

The seedlings were probably 4 years old when they were planted, but the exact age of the seedlings is unknown. Kurdiani (1914) wrote: "During the experiments in 1909 we received seeds of a hybrid larch. The seeds were sown in a nursery. At the present time we have 55 seedlings." He reported also that the progeny of the hybrid *L. decidua* x *L. kaempferi* grew much faster than seedlings of the European and Japanese larch. In the hybrids, however, there were some negative traits not found in the parents. It turned out that seedlings of *L.* x *eurolepis* under the climatic conditions of Pulawy, Poland were more sensitive than *L. decidua* to autumn frosts which frequently injured their tops.

Both plots were in relatively good condition except that some plants were infected with wood canker and could not be cored. A third plot with the progeny of the paternal tree of *L. kaempferi* had been planted in 1914, but no surviving trees could be found (Oleksyn and Giertych 1984).

A nitrogen fertilizer factory that began operation in 1966, 3 km from the experimental are (Fig. 1), emitted toxic substances, which dramatically changed the growth of the forest (Oleksyn et al. 1991) as well as agricultural crops (Siuta 1968; Adamczyk-Winiarska and Krol 1972). The effect of air pollution was eliminated by excluding all tree rings produced after 1965 during the pollution period.

The meteorological data, which were from the city of Pulawy, approximately 3 km south-west from the experimental area, began in 1871 with small interruptions during World Wars I and II and continued to the present day (Mitosek 1961, 1964).

Cores were taken from trees in both plots in the spring of 1984. At the time the mean height was 21.5 ± 3.4 m for European larch and 23.1 ± 2.9 m for the hybrid. As much as 25% of European larches and nearly 50% of the hybrid larches were affected by the canker, so only 15 and 10 cores could be taken from each species respectively. In addition, 5 cores from *L. decidua* and 3 from *L.* x *eurolepis* could not be cross-dated or the measurements were distorted, so they were not processed and included in the standardized chronology.

Sampling and analysis of tree-ring data

The earlywood and latewood widths were measured with the system described by Chalupka et al. (1977) at the Institute of Dendrology in Kornik, Poland. The measurements from all tress were cross-dated through the skeleton plot method (Stokes and Smiley 1968; Fritts 1976). A dating check was made using the computer-assisted method, program COFECHA, developed by R. L. Holmes (Holmes et al. 1986) at the Laboratory of Tree-Ring Research, Tucson, Arizona, USA. The program identifies all locations within each ring series that my have erroneous cross-dating or measurements errors. The original cores and measurements were then re-examined to evaluate all locations with problems and the errors corrected. A second run of COFECHA was used to verify the changes and to assure that all measurements were in the correct order.

Each type of measurement was averaged for all cores of the same species, and the averaged series was standardized (1925–1965) using the computer program INDEX developed by the Tree-Ring Laboratory (Graybill 1979). A yearly growth index is calculated that is free of tree-age relationships and has a mean value of 1.0 (Fritts 1966). A negative exponential function of the following form is fit to each set of averaged measurements (Table 4):

$$Y_t = a\, e^{-bt} + k \qquad (1)$$

where the values of a, b and k vary from series to series depending upon the shape of the curve required to fit the data, e is the base of natural logarithms and Y_t is the expected growth at given year t. The values of t vary from 1 to n.

Ring-width indices for each variant or species were obtained by

$$I_t = R_t / Y_t \qquad (2)$$

where R_t is an average width measurement for year t and Y_t is the same as in Eq. 1 (Graybill 1982). The ring width data for the pollution interval (1966–1983) were not used to estimate the exponential curve and indices in the analysis.

Three statistics that were calculated for the standardized chronologies are standard deviation, first-order autocorrelation and mean sensitivity. The standard deviation measures the variability of the measurements at all wave lengths. High standard deviation generally indicates that the

Table 2. Average total ring width, earlywood width and latewood width (in mm), and percent of latewood for *Larix decidua* and *L.* x *eurolepis*

Species	Period 1925–1934		1935–1944		1945–1954		1955–1965		1925–1965	
	Width	%	Width	%	Width	%	Width	%	Width	%
Ring Width										
L. decidua	3.63	30.3	1.41	41.8	0.78	47.4	1.01	50.5	1.69	37.9
L. x *eurolepis*	3.51	26.8	1.64	38.4	1.10***[a]	43.6	1.09	43.1	1.82	34.6
Earlywood Width										
L. decidua	2.52		0.83		0.41		0.51		1.05	
L. x *eurolepis*	2.58		1.01		0.61***		0.62***		1.19	
Latewood Width										
L. decidua	1.10		0.59		0.37		0.51		0.64	
L. x *eurolepis*	0.94*		0.63		0.48**		0.47		0.63	

[a] Differences between mean ring-widths of the two species were calculated using a t-test with significance level:
* = $P \leq 0.1$, ** = $P \leq 0.05$, *** $P \leq 0.01$

tree-ring series is highly responsive to environmental variables. The first-order autocorrelation assesses relationships with prior growth. Mean sensitivity (ms_x) is a statistic unique to tree-ring analysis. It measures the relative year-to-year ring-width variability or the high-frequency response to variables such as climate. Mean sensitivity is calculated as:

$$ms_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \frac{2(x_{t+1}-x_t)}{x_{t+1}+x_t} \qquad (3)$$

where x_t is a ring width or ring-width index for year t over n number of observations (Douglass 1936; Fritts 1976).

The calculations concerning climatic response in tree rings of larches were made with the RESPONSE program of the Laboratory of Tree-Ring Research, and calculations of multiple regression were made with a simulation program called TREERING developed by Fritts et al. (1991). In the latter program, a stepwise multiple regression analysis selects those variables from a set of candidate variables that reduce the most ring-width index variance. The candidate variables included mean temperature (°C) and total precipitation (mm) for individual months June-December of the year prior to growth and January-September of the year of growth. The form of the equation was:

$$I_t = b_0+b_1 x_{1t}+b_2 x_{2t} \cdot ...b_m x_{mt} \qquad (4)$$

where It is the estimated ring-width index for each year (t); b_1 through b_m are regression coefficients, associated with each of the selected m predictor variables x_1 through x_m, and b_0 is a constant.

Often climatic parameters are highly intercorrelated so that a variable entered into a stepwise multiple regression analysis may block the subsequent entry of other variables that are highly correlated with it. Thus statistical equations are generated with a small set of parsimonious variables with no information about the other less important and supposedly insignificant variables that were not entered into the regression results.

Response functions were developed (Fritts 1976; Guiot et al. 1982) to generate a more complete analysis using principal component regression. The coefficients of a response function express the relative effects of a change of one standard deviation in the causal variables upon ring-width growth. Each coefficient attempts to represent the contribution of that variable to growth independent of the other variables affecting growth. The largest principal components were extracted from the climatic variables and the principal components, along with prior growth, were used in stepwise multiple regression analyses predicting the growth measurements. The significant multiple regression coefficients were converted back to the coordinates of the original climatic variables, and 95% confidence intervals were calculated for each transformed coefficient (response function weight). The same candidate climatic variables used in the multiple regression were used in the response function analysis. More details on this method can be found elsewhere (Fritts 1974, 1976).

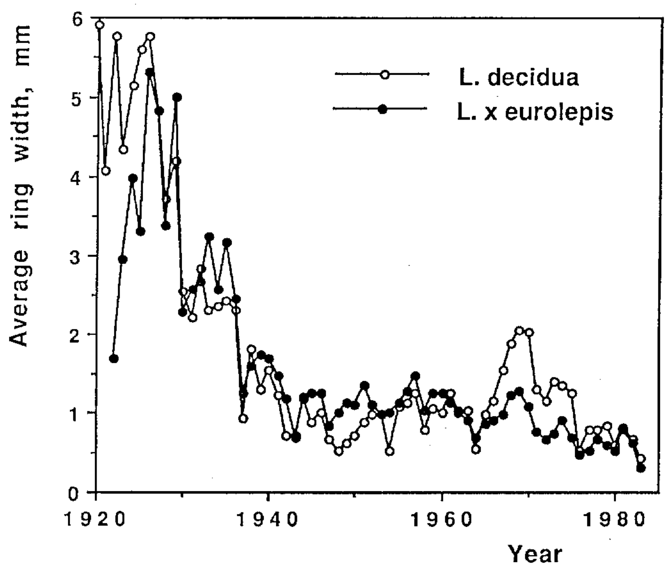


Fig. 2. Average ring width from *Larix decidua* and *L.* x *eurolepis* from Pulawy, Poland plotted as function of year

Results and discussion

The average ring width for the entire period 1925–1965 was 7.1% higher for *L.* x *eurolepis* than for *L. decidua*. However, the difference was not statistically significant (Table 2). Only during 1945–1954 was the difference in the average ring width between those two species statistically significant ($P \leq 0.001$).

Bastien and Keller (1980) noted that the height, diameter and wood volume of *L.* x *eurolepis* were greater than those of either parent. However, Reck (1977) showed that the best growing *L. decidua* families have comparable growth vigor to the hybrid. While Gothe et al. (1980) and Reck (1980) reported that height and diameter growth of *L.* x *eurolepis* was greatest in 10 to 20-year-old trees, in our experiment hybrid larches showed better ring width growth between ages 20 and 35 years but poorer growth at age 10 years or less (Fig. 2). Ring widths in *L.* x *eurolepis* were substantially below those in *L. decidua* for 1922–1925 and they were slightly above those for

Table 3. Correlation coefficients among standardized indices for the three types of measurements within and between species

		L. x *eurolepis*			*L. decidua*	
		TRW[a]	EWW[b]	LWW[c]	TRW	EWW
L. x *eurolepis*	EWW	0.946***[d]				
	LWW	0.601***	0.401**			
L. decidua	TRW	0.793***	0.811***	0.506***		
	EWW	0.735***	0.825***	0.324*	0.943***	
	LWW	0.719***	0.643***	0.671***	0.887***	0.699***

[a] Total ring width
[b] Earlywood width
[c] Latewood width
[d] significance level: * = $P \leq 0.05$, ** = $P \leq 0.01$, *** = $P \leq 0.001$

Table 4. The standardizing equation and chronology statistics for the three measurements from *Larix decidua* and *L.* x *eurolepis*

	L. decidua	*L.* x *eurolepis*
Standardization equation		
TRW[a]	$Y = 6.289e^{-0.08x} + 0.466$	$Y = 4.042e^{-0.045x} + 0.157$
EWW[b]	$Y = 4.937e^{-0.086x} + 0.163$	$Y = 3.304e^{-0.054x} + 0.039$
LWW[c]	$Y = 1.374e^{-0.067x} + 0.308$	$Y = 0.783e^{-0.053x} + 0.316$
Autocorrelation		
TRW	0.555	0.522
EWW	0.634	0.571
LWW	0.314	0.400
Standard deviation		
TRW	0.341	0.298
EWW	0.445	0.379
LWW	0.317	0.218
Mean sensitivity		
TRW	0.265	0.227
EWW	0.277	0.259
LWW	0.321	0.201

[a] TRW – total ring width,
[b] EWW – earlywood width,
[c] LWW – latewood width

L. decidua in 1933–1935. This suggests that the hybrid sampling was not as well adapted to the local environment as the parent. However, only the measurements for 1925–1965 were standardized because the exponential function would not model the 1920–1924 data correctly for *L.* x *eurolepis*.

The within-species variations in earlywood, latewood and total ring-width index are better correlated than between-species variations in these measurements (Table 3), and all correlations are statistically significant. Earlywood width is highly correlated with annual ring width, while latewood widths is not as highly correlated with the other two measurements. This finding supports the observations of Schweingruber et al. (1978) that earlywood and total ring width seem to be relatively independent of the latewood in *L. decidua*, *Pinus sylvestris* and *P. cembra* from subalpine sites in Switzerland.

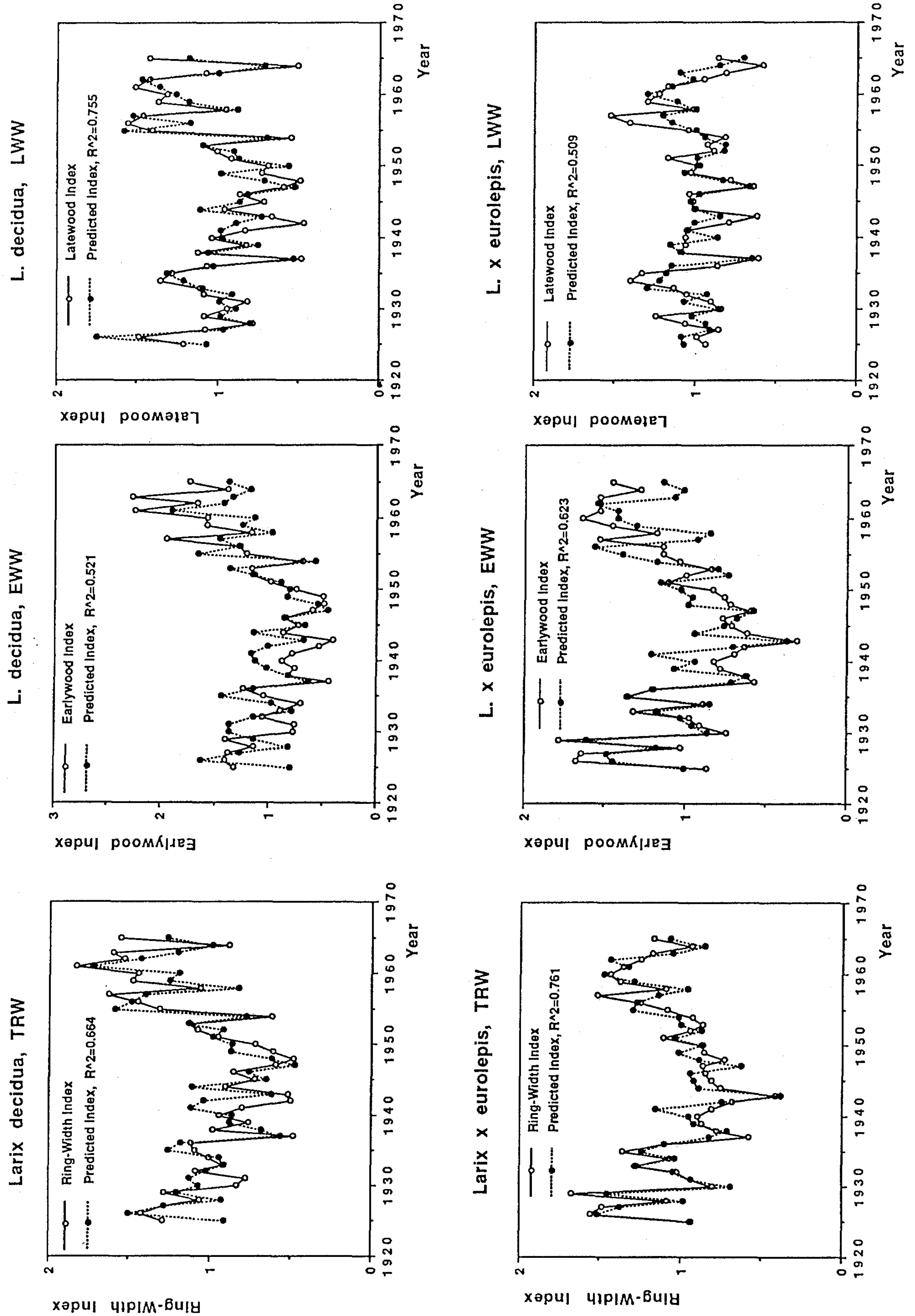
Table 4 presents the basic chronology statistics, along with equations used for standardization. Mean sensitivity values for *L. decidua* are always higher than those for *L.* x *eurolepis*. It is interesting that the latewood of

Table 5. Summary of the significant regression coefficients from equations expressing the effects of climatic factors on chronologies of *Larix decidua* and *L.* x *eurolepis*

Species		Temperature																Precipitation															
	Month	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
L. decidua	EWW[a]											–[d]				–			–		–		+						–			–	
	LWW[b]										+	–	+	+	+				–		–								–			–	
	TRW[c]											–				–			–	–	–		+						–			–	
L. x *eurolepis*																																	
	EWW												+			–				–			+									–	
	LWW		+	+											+	–																	–
	TRW									+			+	+	+	–				–	–		+									–	

[a] Earlywood width
[b] Latewood width
[c] Total ring-width
[d] + Indicates a positive element significant at $P \leq 0.05$ and – indicates a negative element significant at $P \leq 0.05$

Fig. 3. Actual and predicted index values using stepwise multiple regression of earlywood (*EWW*), latewood (*LWW*) and total ring-width (*TRW*) of *L. decidua* and *L.* x *eurolepis* along with the variance reduced



Larix decidua, TRW
Ring-Width Index
Predicted Index, R^2=0.664
Ring-Width Index
Year
L. decidua, EWW
Earlywood Index
Predicted Index, R^2=0.521
Earlywood Index
Year
L. decidua, LWW
Latewood Index
Predicted Index, R^2=0.755
Latewood Index
Year
Larix x eurolepis, TRW
Ring-Width Index
Predicted Index, R^2=0.761
Ring-Width Index
Year
L. x eurolepis, EWW
Earlywood Index
Predicted Index, R^2=0.623
Earlywood Index
Year
L. x eurolepis, LWW
Latewood Index
Predicted Index, R^2=0.509
Latewood Index
Year

Table 6. Summary of the significant response function elements for *Larix decidua* and *L.* x *eurolepis* chronologies in Pulawy, Poland

Species		Precipitation																Temperature																Previous growth		
	Month	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3
L. decidua	EWW[a]													+[d]		−		−	−	−														+	+	
	LWW[b]											−	+	+		−		−	−	−						−			−			−				
	TRW[c]												+	+		−		−	−	−												−		+	+	
L. x *eurolepis*																																				
	EWW	+		−			−	+	−				+	+	+	−				−	−		+									−			+	
	LWW	+	+	+							+		+	+	+		+	−		−	−	−				−		−	−	+	+		−			−
	TRW								−			−	+	+	+	−				−						−								+		

[a] Earlywood width
[b] Latewood width
[c] Total ring-width
[c] + Indicates a positive element significant at $P \leq 0.05$ and − indicates a negative element significant at $P \leq 0.05$

Table 7. Percent variance reduced by response of *Larix decidua* and *L.* x *eurolepis* chronologies from Pulawy, Poland

Species		Related to climate	Related to prior growth	Total
L. decidua				
	EWW[a]	31.6	49.4	81.0
	LWW[b]	77.1	3.8	80.9
	TRW[c]	48.3	29.7	78.0
L. x *eurolepis*				
	EWW	44.8	35.2	80.0
	LWW	74.3	18.1	92.4
	TRW	69.1	16.6	85.7

[a] Earlywood width
[b] Latewood width
[c] Total ring-width

L. decidua has the highest mean sensitivity value, while the latewood of *L.* x *eurolepis* has the lowest mean sensitivity value. The mean sensitivities of all tree-ring parameters were generally higher than those reported by Schweingruber et al. (1978) for *L. decidua* growing in moderately humid subalpine sites in Switzerland. They are also higher than the mean sensitivities for some tree-ring chronologies from coniferous species along the North Pacific coast of the United States and in Georgia (Holmes et al. 1986; Grissino-Mayer et al. 1989), but they are lower than the mean sensitivities for tree-ring chronologies from the arid North American West (Fritts and Shatz 1975).

The standard deviation ranged from 0.218 for latewood of *L.* x *eurolepis* to 0.445 for earlywood width of *L. decidua*. High standard deviations and high mean sensitivities demonstrate the relatively high ring-width variability of the trees growing in this experiment. This variability appears to be connected to the xerophytic nature of the site compared to the range of the species.

The signs of the significant coefficients entered into the multiple regression are shown in Table 5. Many significant coefficients or elements for precipitation are positive in May-July, many for temperature are negative for the prior summer and those for both temperature and precipitation are negative for the current August. Some differences are also apparent between species and type of measurements.

The actual and estimated indices using the equations are presented in Fig. 3. The variability of the three types of indices is well modeled by the regression. The low values in the 1940s appear to be associated with limiting climatic conditions. The equation for latewood of *L. decidua* accounts for the most variance, while the equation for latewood of *L.* x *eurolepis* accounts for the least variance.

Figures 4 and 5 include plots of the response functions. The values of the response functon coefficients express the relative influence of each monthly climatic variable on the width measurement. Coefficients for the effects of growth in 1, 2 and 3 preceding years are shown on the far right (if the effect was significant enough to be entered into regression). A positive value expresses a direct relationship between the variable and growth. A negative value expresses an inverse relationship. The vertical lines delimit the 95% confidence bands of the response function weights. The signs of the significant climatic responses in Figs. 4 and 5 are summarized in Table 6, and the variances reduced are shown in Table 7.

Several inferences can be made from these data. The largest response in all species is a direct relationship between precipitation in May-July and all measurements of ring width. This appears to be a response to water stress and is strongest for latewood and most pronounced in *L.* x *eurolepis*, which generally grows in more moist environments. Also precipitation in March was significant in the response function for latewood of *L.* x *eurolepis*. The second largest response is an inverse relationship between temperatures during July-September of the prior growing season. This may also reflect the importance of water stress, but may also be attributed to temperature effects upon respiration, bud initiation and fruit set which can reduce carbohydrate reserves that in turn could reduce the next year's growth. An inverse response of growth to precipitation and temperature in August of the growing season is also evident. Apparently cool moist conditions at the end of the growing season may reduce ring-width growth. The response functions for latewood (Figs. 4, 5) suggest that high June and July temperatures are more favorable to formation of latewood in *L.* x *eurolepis* than *L. decidua*.

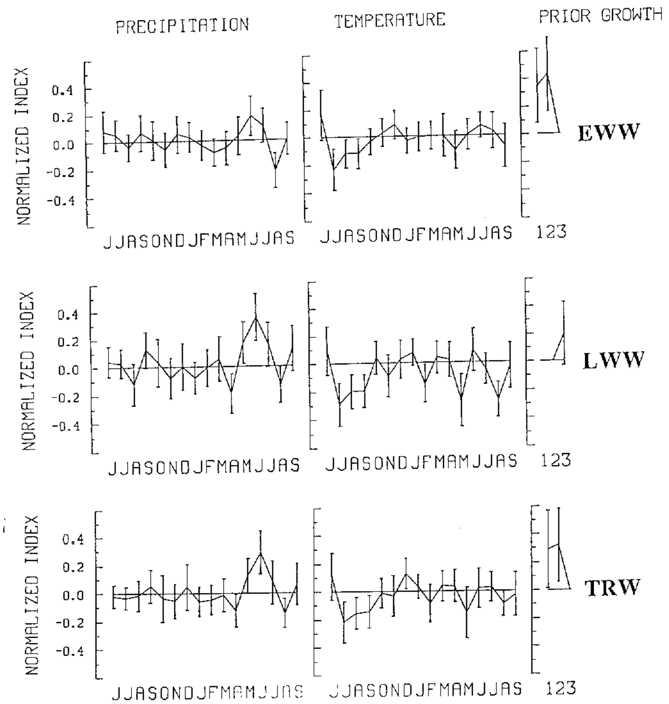


Fig. 4. The response function for earlywood (*EWW*), latewood (*LWW*) and total ring-width (*TRW*) for *L. decidua*. See text for explanation

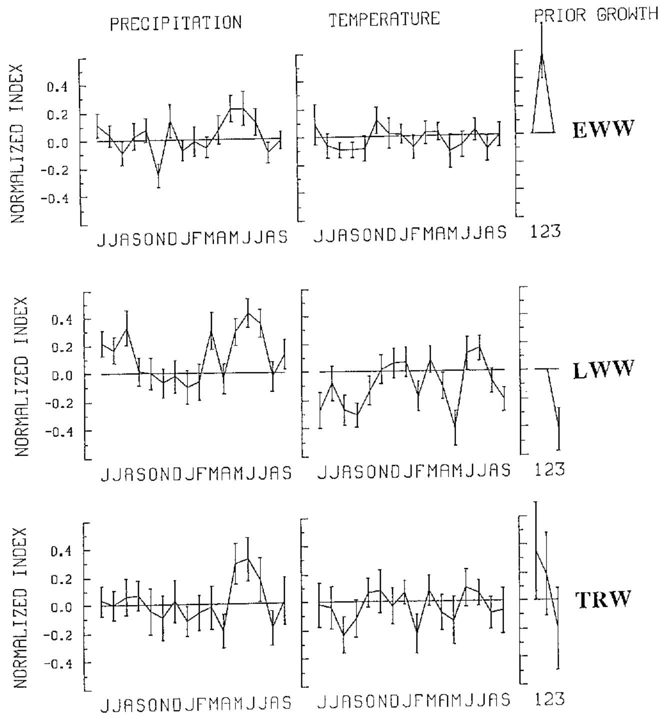


Fig. 5. The response function for earlywood (*EWW*), latewood (*LWW*) and total ring-width (*TRW*) for *L.* x *eurolepis*. See text for explanation

The differences between the multiple regression coefficients and the response function are probably caused by the different ways colinearities among the predictor variables are handled by the two analyses, which prevent variables that are highly correlated with variables in regression from entering the stepwise multiple regression equation (Fritts 1976). All variables are considered in the response function analysis. However, the confidence intervals of the multiple regression may be more reliable than the confidence intervals of the response function results (Cropper 1985).

The dependency of earlywood and latewood on prior earlywood and latewood is not modeled correctly in this particular analysis, as each layer should have been related to the layer that preceded it, i.e. latewood should depend upon earlywood and earlywood depend upon latewood of the preceding year and so on. Ring width, however, is significantly dependent upon the growth for preceding years 1 and 2. Unlike Scots pine (Oleksyn et al. 1991), winter temperatures do not influence ring widths of larch.

The results from this paper support the observations of other workers concerning the high water requirements of larches (for review, see: Oleksyn and Lorenc-Plucinska 1986). For example Polster (1967) reported that the daily rate of transpiration of *L. decidua* is 3.8 g $H_2O g^{-1}$ of needle fresh weight, which is 1.7–1.9 times higher than transpiration in *Pinus cembra, P. strobus* and *P. sylvestris*.

Our observations concerning the high water requirement of hybrid larches in comparison to European larch is in agreement with the observations of Haasemann and Tzschacksch (1986) on 1 to 3-year-old seedlings growing in a partially controlled climate under different soil moisture regimes. They noted that moist conditions were optimal for *L. kaempferi*, intermediate conditions were optimal for *L.* x *eurolepis* and dry conditions were optimal for *L. decidua*.

We observed an increase of growth of both species after 1966, when the nitrogen fertilizer factory in Pulawy started operations (Fig. 2). The ring widths of *L. decidua* were 86.8% higher than the widths estimated from climate, while the widths for *L.* x *eurolepis* were 30.4% higher than those estimated from climate (Oleksyn et al. 1991). This is consistent with the fact that larches are in general relatively resistant to industrial pollution (Bialobok et al. 1984; Sindelar 1984). The beneficial effect on ring width during the first 10 years of pollution may be a fertilization effect of nitrogen compounds, which appear to be required more by larch than by other evergreen woody plants (Matyssek 1986). From 1977 to 1983 growth in larches was equal to or less than predicted. This could be a result of indirect long-term negative effects of a variety of toxic compounds emitted by the nitrogen works. For example, soil analysis performed by Trojanowski (1983) demonstrated that pH of the humus layer of Forest Range Ruda declined from 5.9–6.4 in 1949–1950 to 3.5–4.3 in 1977–1979.

Acknowledgements. This research was supported by the U.S. Information Agency under Fulbright Grant no. 11201 and by the Laboratory of Tree-Ring Research, University of Arizona. The authors thank Jakub Dolatowski from the Institute of Dendrology of the Polish Academy of Sciences for assistance in the coring. R. K. Adams was of great assistance in tree-ring dating, preparation and measurement techniques. G. R. Lofgren, B. J. Richards and P. J. Brem contributed significantly to the data processing analysis, and Barbara J. Molloy and Erin M. Collopy provided much personal assistance.

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