2012

Opposing Growth Trends Created by External Disturbances in Larch Forests of the Mongolian Altai

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Erforsch. biol. Ress. Mongolei (Halle/Saale) 2012 (**12**): 353–363

Opposing growth trends created by external disturbances in larch forests of the Mongolian Altai

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Abstract

If tree-ring series from different trees are merged to a chronology, in order to for example make inferences on climate, these series must be checked for consistency. Statistical parameters, including the *Gleichläufigkeit* (*GL* = coefficient of agreement) and standard *t* value have been applied for this purpose and are usually combined to boost the informative value. We tested the hypothesis that low *GL* and *t* values can, in turn, be used as indicators of external disturbance in a case study in forests of Siberian larch (*Larix sibirica*) in the Mongolian Altai. Since these forests were known to have been subjected to considerable selective logging, we were interested as to whether opposing trends in the radial stem increment between different tree individuals of the same forest stand can be correlated with logging intensity. We found low *GL* and *t* values at high tree stump densities and basal areas. Furthermore, other factors which are interrelated with logging were also correlated with *GL* and *t*. These factors included tree age, the dominance type (dominant versus suppressed position), the competitive pressure by neighbouring trees and stand density. In conclusion, low *GL* and *t* values can be used as indicators of external disturbance. However, the prevailing type of disturbance can only be identified in combination with a study of structural stand traits. In the present case study, the tree stump density combined with *GL* and *t* values are assumed to be good proxies of selective logging intensity.

Key words: logging, *t* value, Gleichläufigkeit, boreal forest, *Larix sibirica*, Altai Mountains

1. Introduction

Tree-ring analysis is an established method for the reconstruction of inter-annual climate variability during the most recent centuries (FRITTS 1976). Some chronologies, which incorporate deadwood that outlasted long periods as construction material or buried by sediments, cover even millennia (NICOLUSSI et al. 2009). The radial stem increment has low priority for trees, as carbon is more readily invested in the foliage, the root system and regeneration (LACOINTE 2000). Therefore, tree-ring width shows a sensitive response on inter-annual variations in climate, which affect carbon assimilation. A prerequisite for inferences on climate from tree-ring chronologies is the recognition and subsequent exclusion of interferences by non-climatic factors. Such factors include the age-related decline in tree-ring width due to the facts that the wood is distributed over a steadily increasing stem circumference and that trees become less productive during senescence (FRITTS 1976, SCHWEINGRUBER 1996). External disturbances also interfere with the climate signal; such disturbances include insect calamities, windfall and snowbreak as well as anthropogenic influences, like logging.

Disturbance rarely affects all trees of a forest stand in the same way or to the same extent. Therefore, the tree-ring series from the individual wood cores are routinely tested for consistency in the inter-annual variability of tree-ring width (WIGLEY et al. 1987). Parameters commonly used to analyze consistency include the *Gleichläufigkeit* (*GL* = coefficient of agreement sometimes called *g* score) and the standard *t* value as measures of congruence among series. *GL* is a qualitative parameter, which counts the years where two tree-ring series have a higher or a lower tree-ring width than in the preceding year in common. The years with opposite trends for radial stem increment are subtracted from this value, and the result is divided by the total number of years (ECKSTEIN & BAUCH 1969). In contrast to *GL*, the *t* value is fully parametric and considers the magnitude of the differences in the radial increment (BAILLIE & PILCHER 1973). While the calculation of mean curves from different tree-ring series requires a high level of consistency, indicated by high *GL* and high *t* values, low *GL* and *t* values found between tree-ring series of a given site can conversely be taken as an indicator of high disturbance.

We were interested in the question how the intensity of past selective logging can be correlated with the occurrence of low *GL* and *t* values and how other parameters, including stand density, tree age, the dominance type of the tree (dominance versus suppression), and the competition by other tree individuals influence the *GL* and *t* values. Therefore, we analyzed the relationship of these factors with *GL* and *t* values in forests of Siberian larch (*Larix sibirica* Ledeb.) in the forest-steppe of the Mongolian Altai. The Mongolian forest-steppe was selected as a case example for our study, as these forests are subjected to spatially highly variable degrees of unsystematic selective logging by the local population (TSOGTBAATAR 2004, ERDENECHULUUN 2006, LKHAGVADORJ et al. 2013). With our study, we aimed at testing the hypothesis that the past logging intensity (measured as the number or basal area of tree stumps), stand density, the dominance and the age of the sample tree as well as the competitive pressure by other trees exert an influence on the consistency of the tree-ring series from different trees within a forest landscape.

2. Material and methods

Study area

Field work was carried out in the Mongolian Altai in the Altai Tavan Bogd National Park in the Dayan administrative subunit (‘bag’) of the province (‘aimag’) of Bayan-Ulgii, western Mongolia, 110 km SW of the city of Ulgii (fig. 1). In the study area, forests occur on north-facing slopes between an elevation of ca. 2000 and 2500 m a.s.l. in contact to true steppes and alpine meadows. Forests usually grow only on the upper, or if an alpine tree line is present, the central part of the mountain slopes. The studied forests were monospecific stands of Siberian larch (*Larix sibirica* Ledeb.). Geologically, the Mongolian Altai is dominated by siliceous rock, including granite and schist. The prevailing forest soils are Leptosols. The study area is located in the zone of continuous permafrost (SHARKHUU 2003).

Climate data used in this study were available from the village of Altai (station ‘Yalalt’, 48°17’ N, 89°31’ E, 2150 m a.s.l.), 40 km east of Lake Dayan Nuur, since 1970; the series was prolongated by the period from 1940 to 1970 applying linear regression analysis (temperature: $r = 0.995$, $P < 0.001$; precipitation: $r = 0.79$, $P < 0.001$) with the help of data from the weather station at Ulgii City (1960 m a.s.l.). The mean annual temperature was -3.4 °C and has increased by 2.1 °C since 1940 ($r = 0.57$, $P < 0.001$); annual precipitation amounted to 120 mm and has remained unchanged.

Sample plots

Six forested sites were selected on the northern flank of a mountain ridge located 2 to 7 km S and SSE of Lake Dayan Nuur (48°23’ N, 88°55’ E). The geographical position and elevation of these sites are compiled in table 1. The distance between neighbouring sites amounted to 2.2 ± 0.5 km. We included all available forest islands on the studied mountain range for this study; thus the selection procedure largely excluded the subjective choice of sites. Relatively moist depressions, which occur locally on the mountain slopes, were deliberately avoided to improve comparability between sites. At each site, three plots each of 20 m × 20 m size were selected. All plots were located at 50 to 100 m distance from the edge in direction of the forest interior. Distances between the three interior plots were ca. 20 m; these three plots were statistically not independent and should provide a broader basis for the data. The field work was carried out in July 2010.

Field and laboratory work for tree-ring analysis

On the 18 plots, all larch trees with a minimum diameter at breast height (dbh; 1.3 m) of 3 cm were sampled; these included 1434 trees (table 1). Wood cores were collected at 1.3 m above the ground using an increment borer of 5 mm inner diameter. The borer was driven into the wood parallel to the contour lines of the mountain slopes to avoid compression wood. Additional data, including trunk diameter, dominance type and intraspecific competition were recorded in the field. Three-point scales were used to estimate the dominance type (dominant, subdominant, suppressed) and the competition (close to neighbouring tree, intermediate distance to nearest tree, relatively large distance to neighbouring trees). All tree diameters were measured, all tree stumps were counted and their diameter was also measured. In the laboratory, annual tree-ring width was measured with a precision of 10 µm on a movable object table (Lintab 6, Rinntech, Heidelberg, Germany), the movements of which are electronically transmitted to a computer system equipped with TSAP (Time Series Analysis and Presentation)-Win software (Rinntech).

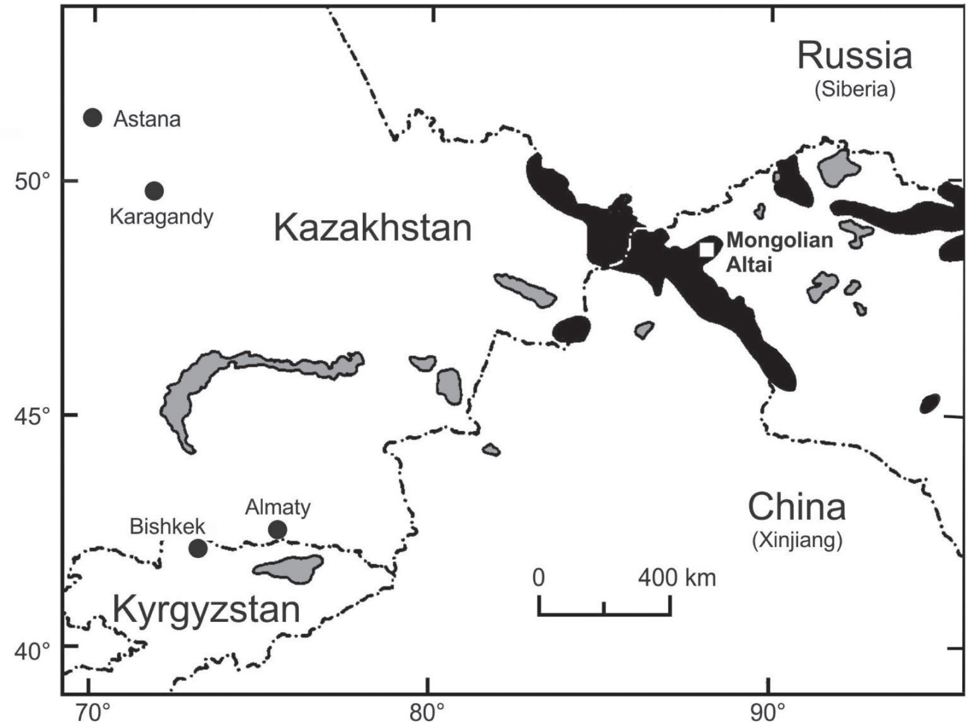

Fig 1: Study area in the Mongolian Altai, western Mongolia.

Analysis of wood cores

The tree-ring data were evaluated with TSAP-Win software. Four age classes (table 1) were distinguished in the analyses including 'very old trees' with the oldest tree ring older than 160 years, 'old trees' (oldest tree ring being between 101 and 160 years old), 'middle-aged trees' (oldest tree ring being between 60 and 100 years old) and 'young trees' (oldest tree ring younger than 60 years old). Age is generally specified as the age of the oldest tree ring ('cambial age') at the sampling height of 1.3 m; c. 10 (at most 20) years should be added to deduce tree age from these age specifications (KÖRNER et al. 2005, SANKEY et al. 2006). In the case of the > 160-year old trees, age was partly underestimated by our methods, because the core was rotten and incomplete in 13 % of these trees. These incomplete cores were still considered for analysis, because we did not perform any extensive interpretation on the absolute age of the oldest trees.

Tree-ring series were controlled for missing rings and false rings during crossdating, as especially missing tree rings can be relatively common in the semiarid environment of Mongolia at the drought limit of forests. Crossdating was done separately for the age class using *GL* and *t* values; GL values > 60 % ($P \leq 0.05$) and *t* values >3 were accepted for merging tree-ring series to chronology. To examine the correlation of *GL* and *t* values with structural and tree population parameters, trees were grouped in four classes according to *GL* and *t* values (table 2). Tree-ring series were standardized using the equation $z_i = w_i/m_i$ with z_i being the annual tree-ring index, with w_i the observed tree-ring width, and m_i being the 5-moving average of year i.

Statistics

Arithmetic means ± standard errors are presented throughout the paper. Data were tested for normal distribution with the Shapiro-Wilk test. Bivariate correlations were analyzed by calculating Pearson correlation coefficients. The significance of differences between more than two means of normally distributed data with equal variability was tested with Duncan's multiple range test. The effect of age, plot, dominance, competition on the *t* and *GL* was tested with analyses of variance (ANOVA) using the SAS 9.13 software (SAS Institute Inc., Cary, North Carolina, U.S.A.).

Fig. 2: Example of one of the studied forests of Siberian larch in the Mongolian Altai.

3. Results

Basic characteristics of tree-ring series and stand structure

Most tree-ring series had both *GL* > 60 % and *t* > 3 (group T4 according to table 2) and were, thus, acceptable for building tree-ring chronologies (table 1). An example for a tree-ring chronology from the study area is given in fig. 3. The percentage of trees of the group T4 varied in the six study sites between 52 and 72 % (table 1). Between 4 and 12 % of the tree-ring series had high *t* values > 3, but low *GL* values < 60 % (group T3). Conversely, 9 to 30 % of the tree-ring series had low *t* values < 3, but high *GL* values > 60 % (group T2). In 7 to 14 % of the tree-ring series, both the *t* (< 3) and *GL* (< 60 %) were low (group T1).

Table 1: Frequency distribution of sample trees (all *Larix sibirica*) in the groups T1 to T4 (definition see table 2) in different age classes along with the number of samples (*N*) and the mean, minimum and maximum cambial ages

	Samples		**Age class (yr)**				**Cambial age (yr)**		
	N	**%[a]**	**> 160**	**101-160**	**60-100**	**< 60**	**mean**	**min.**	**max.**
Site 1 (48°14'39" N, 88°57'0" E, 2375 m a.s.l, *N* = 155 trees)									
T1	13	8	0	0	1	12	37	26	88
T2	25	16	0	0	6	19	47	30	75
T3	6	4	0	0	1	5	42	31	86
T4	111	72	8	3	80	20	83	30	270
Site 2 (48°15'16" N, 88°54'25" E, 2335 m a.s.l, *N* = 197 trees)									
T1	27	14	0	8	6	13	73	28	126
T2	31	25	0	1	5	25	46	24	124
T3	10	5	1	1	0	8	79	44	259
T4	129	66	7	23	14	85	75	29	254
Site 3 (48°15'35" N, 88°54'11" E, 2300 m a.s.l, *N* = 257 trees)									
T1	36	14	5	10	13	8	110	39	435
T2	78	30	3	10	42	23	79	44	221
T3	9	4	3	2	2	2	132	57	307
T4	134	52	4	32	62	40	86	40	434
Site 4 (48°16'3" N, 88°51'35" E, 2320 m a.s.l, *N* = 246 trees)									
T1	37	15	4	9	7	17	87	36	221
T2	33	13	0	3	10	20	67	39	131
T3	26	11	5	5	5	11	102	31	275
T4	150	61	14	37	20	77	89	31	288
Site 5 (48°15'12" N, 88°50'17" E, 2375 m a.s.l, *N* = 242 trees)									
T1	25	10	5	1	18	1	102	38	348
T2	21	9	0	5	12	4	84	29	150
T3	30	12	0	3	25	2	82	33	119
T4	166	69	14	7	119	27	93	27	343
Site 6 (48°14'59" N, 88°55'57" E, 2305 m a.s.l, *N* = 337 trees)									
T1	25	7	0	2	15	8	69	40	110
T2	59	18	1	2	36	20	68	32	230
T3	33	10	6	1	14	12	101	36	318
T4	220	65	19	6	112	83	81	36	322

[a] Percentages were calculated separately for each site.

The densities and basal areas of live trees and tree stumps differed strongly between the sites (table 3). The stand density varied between 1300 and 2860 trees ha^{-1}. The density of tree stumps was relatively high in comparison with the density of live trees; the stump density varied between 610 and 1580 stumps ha^{-1}. The mean ratio of the density of live trees to the density of tree stumps was 1.0 ± 0.2. The basal areas of live trees did not significantly differ between the sites despite the marked variation in stand densities, indicating that the same amount of carbon was distributed over few large trees or many small trees, respectively.

Table 2: Definitions of tree groups according to the consistency of tree-ring series estimated with *t* and *GL* values

	definition		observed *t*			observed *GL*		
	t	*GL*	mean	min.	max.	mean	min.	max.
T1	< 3	< 60	1.5 ± 0.1	0.1 ± 0.0	2.8 ± 0.	51 ± 1	39 ± 1	59 ± 0
T2	< 3	> 60	1.8 ± 0.1	0.1 ± 0.0	2.9 ± 0	68 ± 0	60 ± 0	80 ± 1
T3	> 3	< 60	5.8 ± 0.5	3.2 ± 0.1	11 ± 2	54 ± 1	47 ± 2	59 ± 0
T4	> 3	> 60	7.9 ± 0.3	3.0 ± 0.0	28 ± 4	71 ± 1	60 ± 0	99 ± 2

Table 3: Stand and tree stump densities and basal areas in the studied larch forests[a]

site	density (N ha^{-1})		basal area (m^2 ha^{-1})		ratio trees : stumps	
	live trees	stumps	live trees	stumps	density	basal area
1	1300 ± 388 a	1583 ± 608 a	26 ± 13 a	29 ± 14 ac	1.1	1.2
2	1650 ± 270 a	608 ± 42 a	36 ± 8 a	10 ± 6 a	0.3	0.4
3	2142 ± 371 ab	2242 ± 1132 a	37 ± 12 a	66 ± 7.6 b	1.7	1.1
4	2042 ± 68 ab	1083 ± 282 a	39 ± 13 a	30 ± 9 ac	0.8	0.5
5	2042 ± 341 ab	1167 ± 469 a	42 ± 7 a	61 ± 13 bc	1.4	0.6
6	2858 ± 257 b	925 ± 240 a	49 ± 7 a	36 ± 8 abc	0.7	0.3

[a] within a column, means followed by the same letter, do not differ significantly (Duncan's multiple range test, $P \leq 0.05$, $df = 5$).

Table 4: Results of four-way ANOVA analyzing the effects of tree age, dominance, competition and plot on *t* for tree-ring series and separately for the tree-ring series of the groups T1-T4[a]

	df	all trees	*df*	T1	*df*	T2	*df*	T3	*df*	T4
total	79	15.6*** (R^2 = 0.48)	54	1.0 (R^2 = 0.33)	52	1.0 (R^2 = 0.21)	41	5.0 (R^2 = 0.74)	77	15.0*** (R^2 = 0.58)
age	3	118***	3	0.2	3	0.8	3	41***	3	140***
dominance	2	60***	2	0.3	2	0.5	2	1.9	2	19***
competition	2	3.0*	2	0.2	2	0.0	2	3.1*	2	0.7
plot	17	15***	5	1.5	17	1.0	16	2.2**	17	11***
age x **dom.**	6	11***	4	1.5	3	0.4	2	1.2	6	4.9***
dom. x **comp.**	4	1.7	3	0.3	3	1.5	1	1.9	4	0.3
age x **plot**	45	9.6***	25	0.8	22	1.1	15	2.4**	43	11***

[a] *F* value and *P* (*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$).

Factors influencing t and GL values

The results of four-way ANOVA showed that the classes of tree age and dominance as well as the plot exerted a significant influence on *t* (table 4) and *GL* (table 5). The competition with neighbouring trees had an additional effect on *t*. The effects of these stand-internal factors decreased from the tree-ring series with high *t* and high *GL* (group T4) to the tree-ring series with low *t* and low *GL* (group T1) for both *t* (Table 4) and *GL* (table 5). The age classes exerted the greatest effect in both ANOVAs. In linear regression, the absolute values of tree age were positively correlated with *t* (r = 0.40, $P < 0.001$), but indifferent to *GL*. Suppressed trees were more frequent in the groups T1 and T2 than in the other groups (fig. 4). This trend occurred in all age classes, but was most apparent in the very old and old trees. In accordance with the low (*t* values, table 4) or lacking (*GL*, Table 5) significance of the competition type in the ANOVA, the frequency distribution of the individual competition types hardly exhibited any differences between the groups T1-T4 (fig. 5).

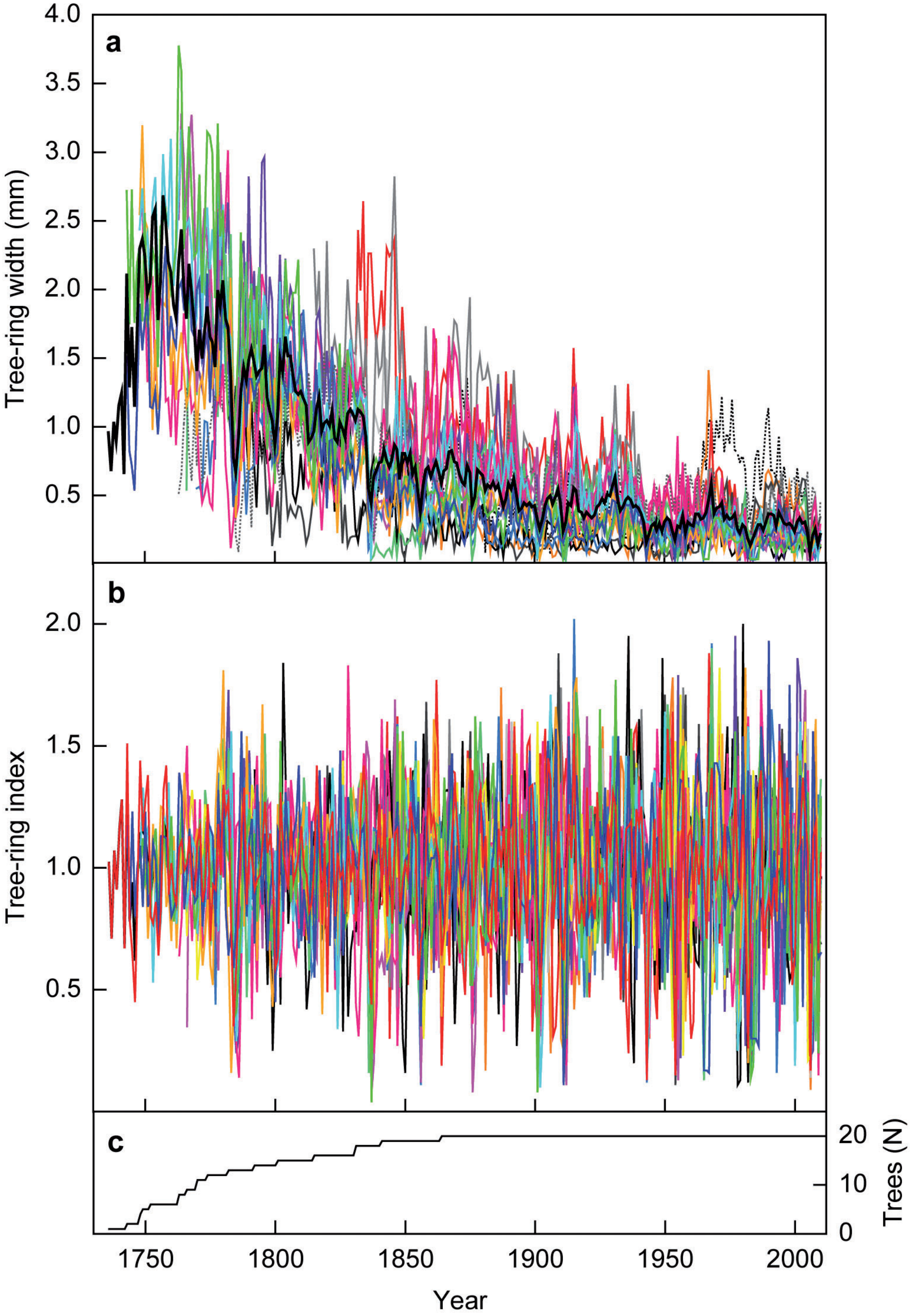

Fig. 3: Tree-ring series of 20 very old (> 160-yr old) trees from site 4. The mean curve is printed in black bold, whereas the colour lines represent the tree-ring series from the 20 individual trees: (a) tree-ring width, (b) tree-ring index, (c) number of samples.

Table 5: Results of four-way ANOVA analyzing the effects of tree age, dominance, competition and plot on *GL* for tree-ring series and separately for the tree-ring series of the groups T1-T4[a]

	df	all trees	*df*	T1	*df*	T2	*df*	T3	*df*	T4
total	79	3.8*** (R^2 = 0.18)	54	1.4 (R^2 = 0.41)	52	1.7** (R^2 = 0.31)	41	1.2 (R^2 = 41)	77	4.1*** (R^2 = 0.28)
age	3	26***	3	2.2	3	13***	3	3.8**	3	49***
dominance	2	19***	2	0.2	2	0.3	2	2.9	2	7.4***
competition	2	0.9	2	2.0	2	0.6	2	0.2	2	0.1
plot	17	4.7***	15	2.3**	17	1.5	16	1.1	17	3.7***
age x **dom.**	6	1.6	4	0.6	3	0.7	2	0.7	6	1.6
dom. x **comp.**	4	0.4	3	0.0	3	0.1	1	0.4	4	0.3
age x **plot**	45	2.1***	25	1.1	22	0.9	15	0.8	43	1.8***

[a] *F* value and *P* (*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$)

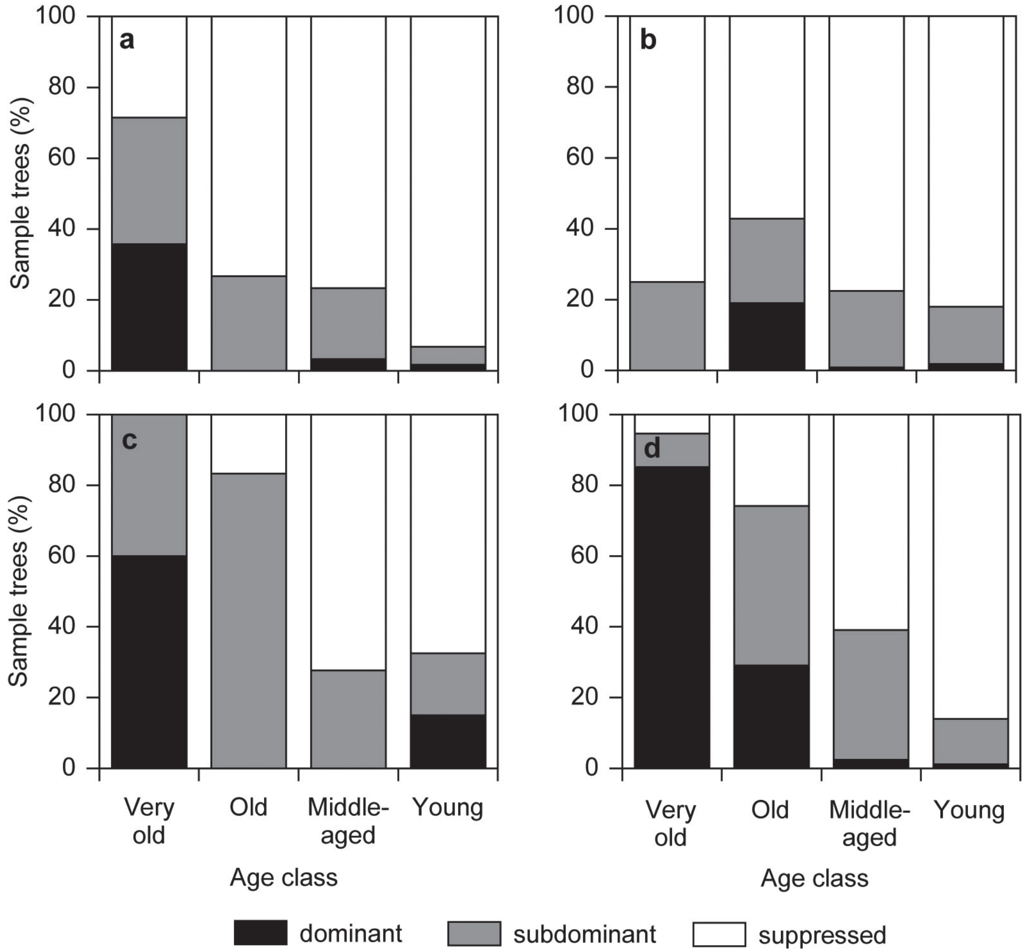

Fig. 4: Frequency distribution of trees in dominance types and age classes in (a) group T1, (b) group T2, (c) group T3, and (d) group T4.

Table 6: Pearson correlation coefficients for the relationship of *GL* in the groups of trees with *GL* > 60 % (=T2 and T4) and stand and tree stump densities and basal areas[a]

	T2	T4
stand density	-0.34	-0.45
stump density	-0.52*	-0.58*
tree basal area	-0.46*	-0.45
stump basal area	-0.48*	-0.45

[a] *$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$

Table 7: Pearson correlation coefficients for the relationship of the number of trees in the groups T1 to T4 with stand density, tree basal area and tree stumps density[a]

	stand density			basal area	stump density
	all trees	> 100 yr	< 100 yr		
T1	0.42*	0.54*	0.18	0.57**	0.38
T2	0.54**	0.32	0.39	0.55**	0.10
T3	0.62**	-0.13	0.66**	0.24	0.44*
T4	0.85***	-0.18	0.89***	0.22	0.26

[a] *$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$.

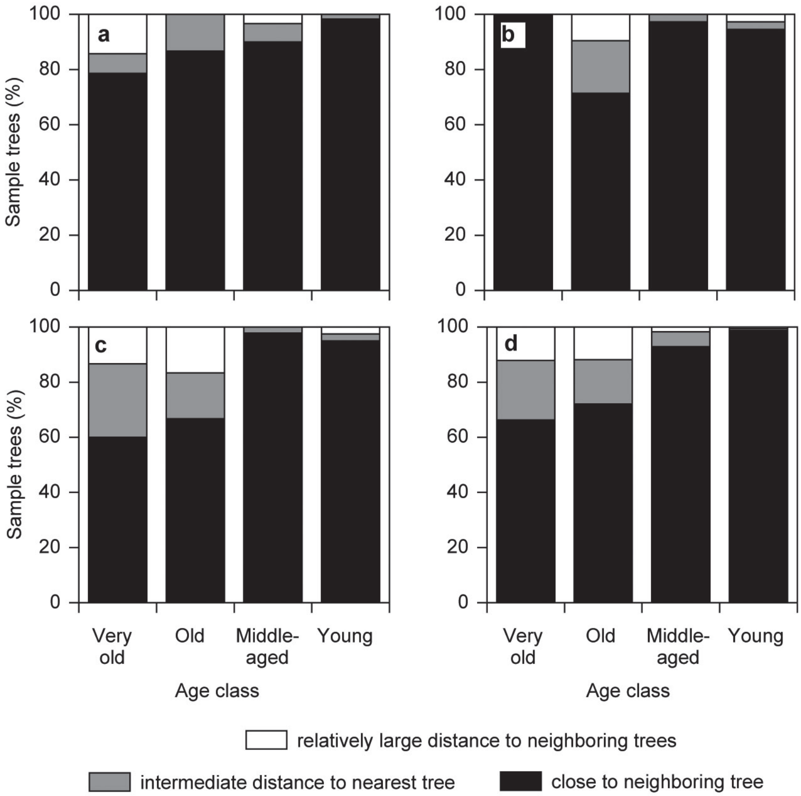

Fig. 5: Frequency distribution of trees in competition and age classes in (a) group T1, (b) group T2, (c) group T3, and (d) group T4.

Linear regression also showed that *GL* in the groups of tree-ring series with *GL* > 60 % (i.e. groups T2 and T4) was negatively correlated with stump and stand densities and basal areas (table 6); similar correlations with *t* were not found. The total number of trees in the groups T1 to T4 was positively correlated with stand density (table 7). If this analysis was done for different age groups, different results were found for the trees which were either less or more than 100 yr old. The total number of trees which belonged to group T1 increased with stand density in trees with an age of > 100 yr, but not < 100 yr. By contrast, the number of trees in the groups T3 and T4 was positively correlated with stand density in the case of young (< 100-yr old), but not of old (> 100-yr old) trees. The total number of trees in the groups T1 and T2 increased with the stand basal area, whereas the number of trees in the groups T1 to T4 was more or less unrelated to stump density.

4. Discussion

Structural traits of the forest stands were clearly related to the consistency between the tree-ring series growing in the same forest. Both the *t* value and *GL*, which are two widely used measures to quantify the consistency between two tree-ring series, were correlated with structural parameters. These parameters included the tree stump density and the stump basal area, which are the result of past selective logging. Stand density, the tree basal area, the dominance type, the intensity of competition by neighbouring trees, and tree age also exerted an influence on *t* and *GL*. All these parameters are interrelated with external disturbance and may depend on logging. Logging results in reduced tree age, because young trees fill the emerging canopy gaps. The removal of mature trees and their replacement by young growth results in higher stand density and increases the tree stump density. Thus, these factors result in lower *t* and/or *GL*.

In the studied larch forests of the Mongolian Altai, the known stand history clearly attributes the occurrence of opposite growth trends within the same forest primarily to unsystematic selective logging, which has been intensified after the transition from centrally managed to market economy after 1990 (LKHAGVADORJ et al. 2013). However, there are also other external disturbances conceivable which might have the same effect. In the Mongolian forest-steppe, these disturbances, first of all include insect calamities (HAUCK et al. 2008) and fire (OTODA et al. 2012). The most important source of tree damage and reductions of the annual stem increment by insects in the Mongolian forest-steppe is herbivory by gypsy moths (*Lymantria dispar* L.) (DULAMSUREN et al. 2010). In the Mongolian Altai, however, it is apparently too cold for heavy infestation by this species. Windfall and snow break are other relevant sources of external disturbance, which might affect *t* and *GL*; however, based on our field observations, these factors seem to be of much lower significance than logging, fire and insect outbreaks in the Mongolian forest-steppe.

In conclusion, low scores of *t* and *GL*, which are undesirable for calculating tree-ring chronologies (i.e. merging individual tree-ring series to a mean curve) and for reconstructing the climatic variability, can be used as indicators of external disturbance. The kind of external disturbance, including logging, fire or insect calamities can be assessed by analyzing structural forest traits and also by interpreting the tree-ring series themselves.

Acknowledgments

The study was funded by a grant of the Volkswagen Foundation to M. Hauck, Ch. Dulamsuren and Ch. Leuschner for the project “Forest regeneration and biodiversity at the forest-steppe border of the Altai and Khangai Mountains under contrasting developments of livestock numbers in Kazakhstan and Mongolia”. We are thankful to the Altai Tavan Bogd National Park (Ulgii) for permissions to carry out the field work. B. Jadambaa, Kh, Ganbaatar, D. Sain-Dondov, B. Bat-Enerel, Yo. Eroolt are thanked for his help during field work. B. Raufeisen (Göttingen) prepared the map. Prof. Dr. M. Hauck (Göttingen) is thanked for comments on the manuscript.

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