Supporting Information for

Poleward migration of the destructive effects of tropical cyclones during the last century

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Supporting Information

Study localities, tree-ring network, cross-dating and sample selection.

Study localities. The age of studied trees was not uniform along the gradient as it is basically impossible to compare forests with similar age structure across such a large gradient. It is important to realize that disturbances are responsible for the age structure of the forests. Subjective selection of forest stands or subset of data with similar size or age structure would bias analyses (75). However, we did not find significant relationships between the age structure and the length of period preceding canopy disturbance (mean age for all individuals and mean age for trees established before and after 1920 at individual localities was tested; $p>0.05$). We performed intercorrelations tests between the canopy disturbance chronologies (Fig. S4) and we found significant correlations between some of them, especially between the localities on the Korean peninsula (Table S5). This was expected as TC activity is higher in the southern latitudes and thus there is higher probability to show similar TC imprint, especially in 5-year intervals (5- or 10-years intervals are commonly used for release detection (61)). There is a natural decrease in correlation between more distant localities. However, lower correlation values towards the north are induced by lower TC activity at the northern latitudes leading to higher variability in TC tracks affecting these latitudes (compared to southern localities where TC tracks have more similar trajectories).

Tree-ring network, cross-dating and statistical analyses. During the 2004-2016 period, core samples were collected from all stems (>10 cm DBH) in permanent research plots at a height of 0.5-1 meter above the ground surface using a steel increment borer. This sampling strategy is free of bias induced by sampling design (75). As we aimed to reconstruct the length of period preceding the canopy disturbance, which enables individual trees to reach the canopy, only canopy trees were sampled and analysed in this study. The cores were dried and a thin layer of wood was sliced from each core using a core microtome (76) to highlight the tree-ring boundaries. Rings were counted from pith to bark and tree-ring widths were measured to the nearest 0.01 mm using the TimeTable measuring device and PAST5 software (http://www.sciem.com). Ring sequences were first visually cross-dated (77) and consequently statistically verified by the percentage of parallel variation ($p < 0.05$, Gleichläufigkeit; see Eckstein and Bauch (78)) and the similarity of growth patterns between individual series (Baillie-Pilcher's t-value; see Baillie and Pilcher (79)).

Sample selection. The main objective of this study was to determine the length of period preceding canopy disturbances, which enable individual trees to reach the canopy, and to investigate if the length of period varied in space (latitudinal gradient) and time (before and after 1920). It was therefore critical to use only samples with preserved inner tree rings, i.e. the tree rings formed shortly after tree establishment, as this is the crucial part of tree life for the identification of canopy accession strategies. Thus, for this study we used increment cores: 1) reaching the pith or 2) with an arc of the inner rings. Consequently, partial cores (which did not contain either pith or an arc) were excluded from this study as information about the early stage of individual tree growth was missing and it is impossible to precisely determine growth patterns of missing inner rings (80). Thus, for final analyses 1207 tree cores were selected from canopy trees and containing the pith or the arc.

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Growth release identification. The used technique of radial-growth averaging criteria developed by Nowacki and Abrams (59) is one of the most common and generally used dendroecological techniques for the reconstruction of canopy disturbances by the detection of growth-release events (61), i.e. an abrupt and sustained increase in the radial growth induced by improved light conditions after the death of neighbouring tree(s). This method was selected for several reasons despite the existence of newer methods developed in the last decades (e.g. 62, 81-83):

1) The radial growth averaging method (59) did not require a large number of tree-ring measurements per individual species (± 50.000 ring width measurements) (84) compared to the boundary-line method (62, 85). This will lead to removing less abundant species from analyses and consequently loosing important information and introducing unwanted noise with species selection.

2) Detail knowledge of growth responses of individual species, which naturally includes subjectivity, is not required compared to the absolute-increase method (82).

3) Open source software (61) is available for the selected method compared to the time-series analysis with intervention detection (81), which limits examination of this method over larger areas and higher number of species to increase confidence for reliable and wider application of this method.

4) International Tree-Ring Data Bank (86) does contain only one record for our study area compared to thousands records available for North America or Europe. Such records could eventually help to fulfil requirements of dataset for computation of absolute-increase threshold (82) or boundary-line (84). However, even if such records were available, there would be other problems which would eventually prevent utilization of these methods (see 84, 87-90)).

In the selected approach (59), the average radial growth over the preceding 10-year period, M_1 (including the target year), and the average radial growth over the subsequent 10-year period, M_2 (excluding the target year) were calculated. The percentage growth change ($\%GC$) is obtained by: $\%GC = [(M_2 – M_1)/M_1] * 100$. To cover whole life-span (tree-ring record) of individual trees, we combined radial-growth averaging criteria (59) with gap origin detection (60, 91) for detection of canopy disturbances (63), which enabled individual trees to reach the canopy. A rather strict threshold (83) of 100% growth change was applied for release identification and it was considered as release only if it was sustained above the given threshold for ≥ 7 years (63). The most intense release was considered as indication of disturbance responsible for canopy accession of trees (60), i.e. canopy disturbance. There are also trees which did not show an abrupt growth increase in radial growth, i.e. with flat or ambiguous growth patterns (60, 64). These individuals did not fulfil our criteria for two reasons: 1) the interpretation of such trends is not unequivocal (64) and 2) it is impossible to determine the year of canopy accession. Thus, such trees were excluded from subsequent analyses.

We aimed to categorize trees with imprint of past canopy disturbance according to the length of period needed for the canopy accession. Previous studies working with long-term growth trends defined individual growth trends but did not usually use categorization according to the year of detected disturbance with regard to the tree age. Hence, there are no generally accepted thresholds to classify trees for the purpose of our study. Thus, we adopted a threshold of 50 years as previously done by Rentch, Fajvan and Hicks (92) and we added a threshold for the gap origin trees of 15 years to have three distinct groups reflecting different disturbance conditions.

Division of the dataset for investigation of temporal stability. Only locations with > 10 trees present in individual periods (before and after 1920) were included in the analyses of temporal stability. Minimum sample size of 10 trees was previously shown as sufficient in dendroecology for obtaining the community response (63, 93-95) (even the lower sample size shows meaningful results for community level (96)). It is important to note that this study did not aim to identify the exact year when TC change started. Our goal was to compare two longer periods (one which includes the documented changes in TC activity (66) and another which precedes the first period and represents “pre-documented stage” of TC activity) and identify the stability/variability in the growth response between these two periods, which will reflect the long-term change in TC activity. As we applied radial-growth averaging criteria (59) using running means over two 10-year periods (see section above), we could not calculate the disturbance history for the last 10-years of the individual tree-ring series (there is the same limitation for the first 10-years of the series, however, this part was covered by including gap origin detection (60, 91) to our analysis; see section above). In addition, we based our analyses on strict criteria and release was identified only for abrupt growth change sustained for at least 7 years (see section above). Hence, a disturbance chronology could not be calculated for the last 17 years and thus last 5-year interval in our disturbance chronologies for all sites was 1980-1984 (this is typical for tree-ring based disturbance detection studies (see 27, 61, 63, 97)) and this is also the last year of period after 1920. Thus, our study provides information for time span preceding previously documented poleward migration of TCs based on reliable, but short-term, instrumental records (16-18).

Supporting Figures

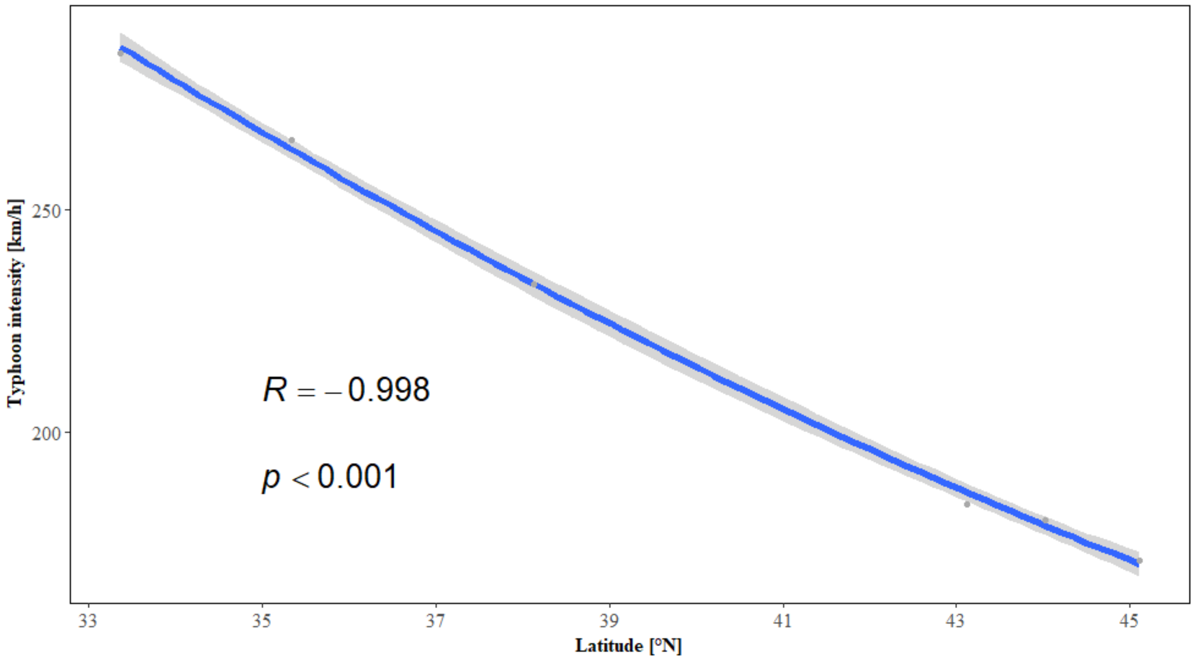
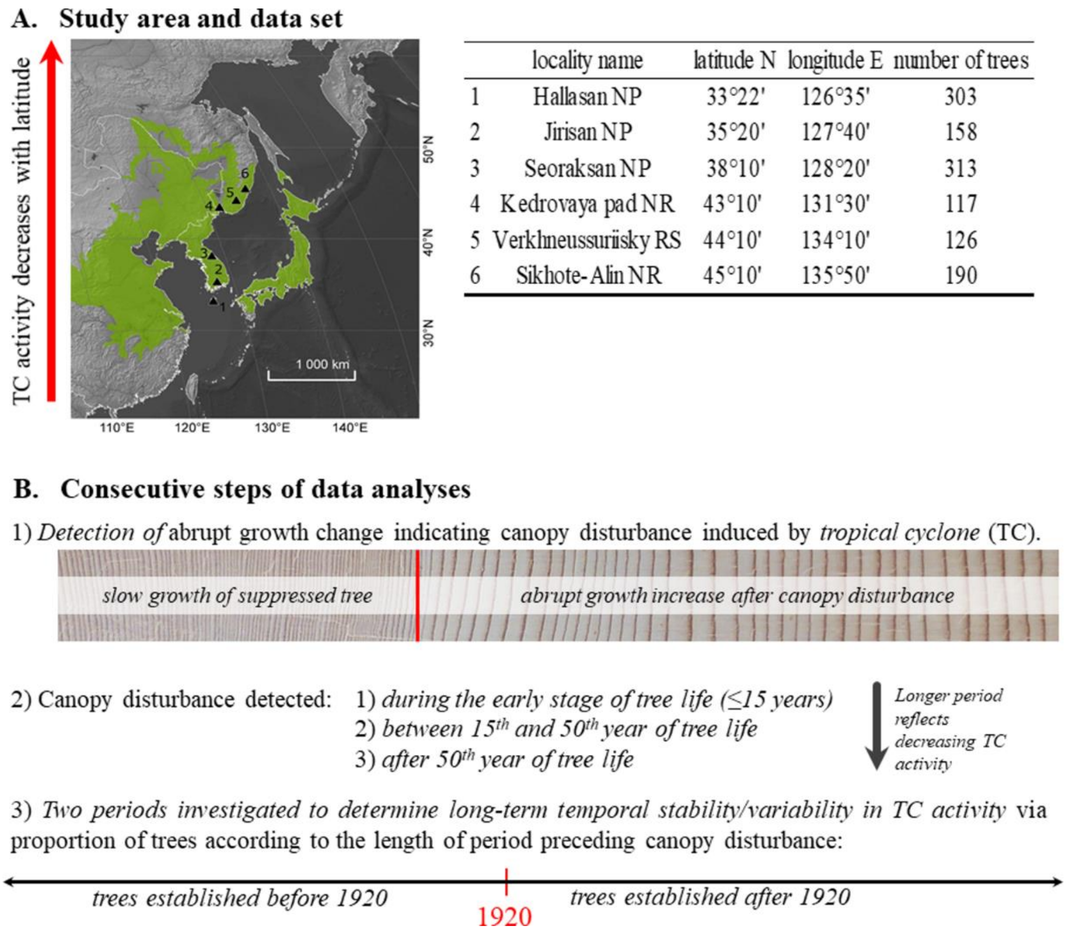
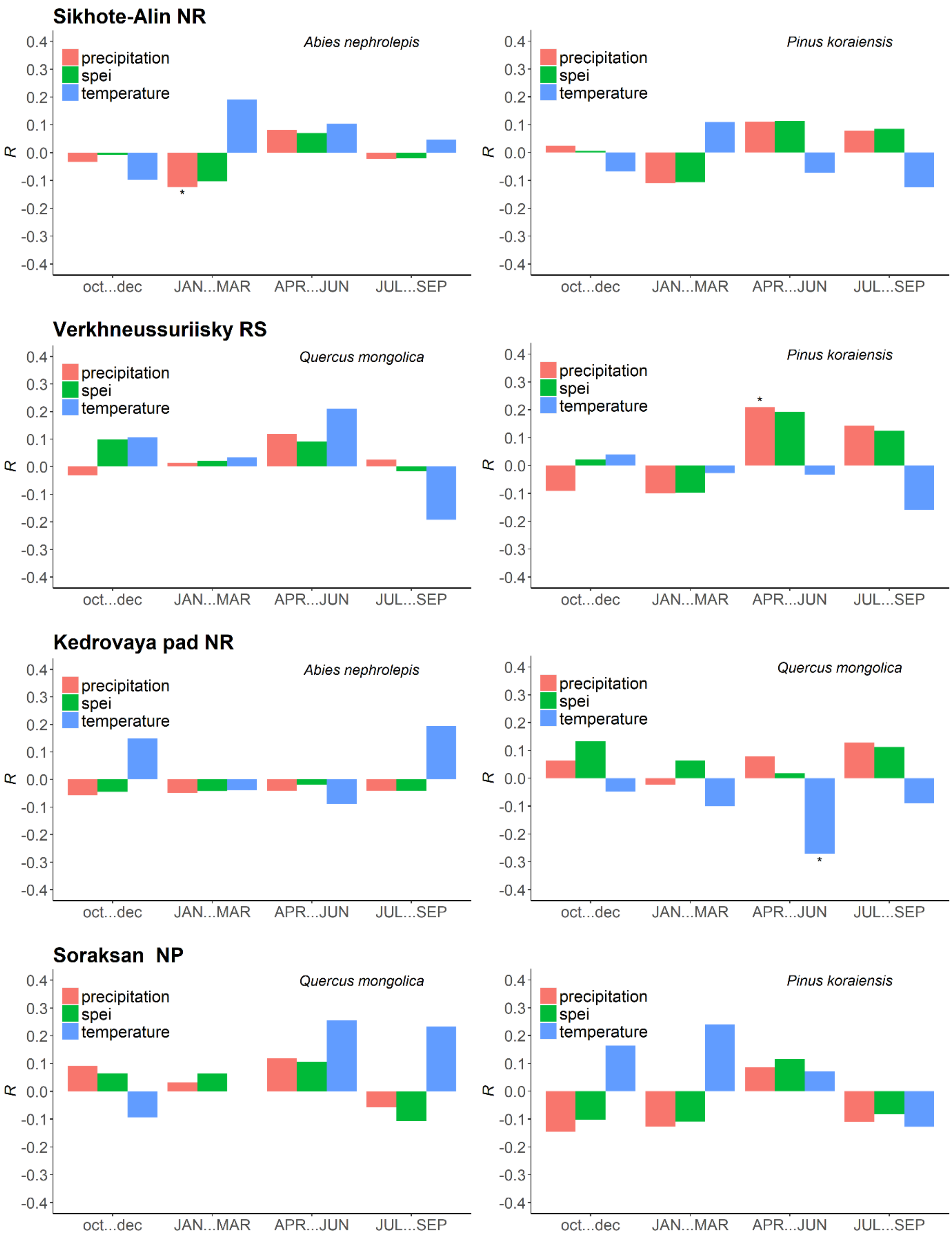


Fig. S1. The relationship between latitude and TC intensity for our study area. Individual study sites (dots) fitted by robust fitting of linear models (blue line) with 95% two-side confidence intervals (shading) are shown as well as Pearson's correlation coefficient (*R*) and level of significance (*p*). Similarly, a significant relationship was found for TC frequency ($p < 0.05$, $R = 0.843$). TC intensity shows 250-year return period windspeeds based on "Cyclone Wind 50-year return period" dataset (compiled by UNEP/GRID-Geneva on the basis of IBTrACS source data (74)). TC frequency was derived from the "Tropical cyclones best tracks 1970-2011" dataset, showing the number of TC events scaled to 100 years.



	locality name	latitude N	longitude E	number of trees
1	Hallasan NP	33°22'	126°35'	303
2	Jirisan NP	35°20'	127°40'	158
3	Seoraksan NP	38°10'	128°20'	313
4	Kedrovaya pad NR	43°10'	131°30'	117
5	Verkhneussuriisky RS	44°10'	134°10'	126
6	Sikhote-Alin NR	45°10'	135°50'	190

Fig. S2 Schema with basic information about the study area, data set and data analyses. (A) The green area shows the distribution of biome temperate broadleaf and mixed forests in NE Asia (adapted from Olson, et al. (52) and Kuennecke (53)) and black triangles indicate the study sites along the gradient of decreasing TC activity. Numbering of the study sites refers to the locality information on the right site (for more information see Table S4). (B) Summary of the main steps of data analyses with (1) an example of an individual tree-ring series showing canopy disturbance, (2) three groups of trees according to the length of period preceding canopy disturbance reflecting different TC activity, and (3) division of the dataset for investigation of temporal stability of TC activity.


Sikhote-Alin NR
Abies nephrolepis
Pinus koraiensis
Verkhneussuriisky RS
Quercus mongolica
Pinus koraiensis
Kedrovaya pad NR
Abies nephrolepis
Quercus mongolica
Soraksan NP
Quercus mongolica
Pinus koraiensis
precipitation
spei
temperature
R
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
*
oct...dec
JAN...MAR
APR...JUN
JUL...SEP

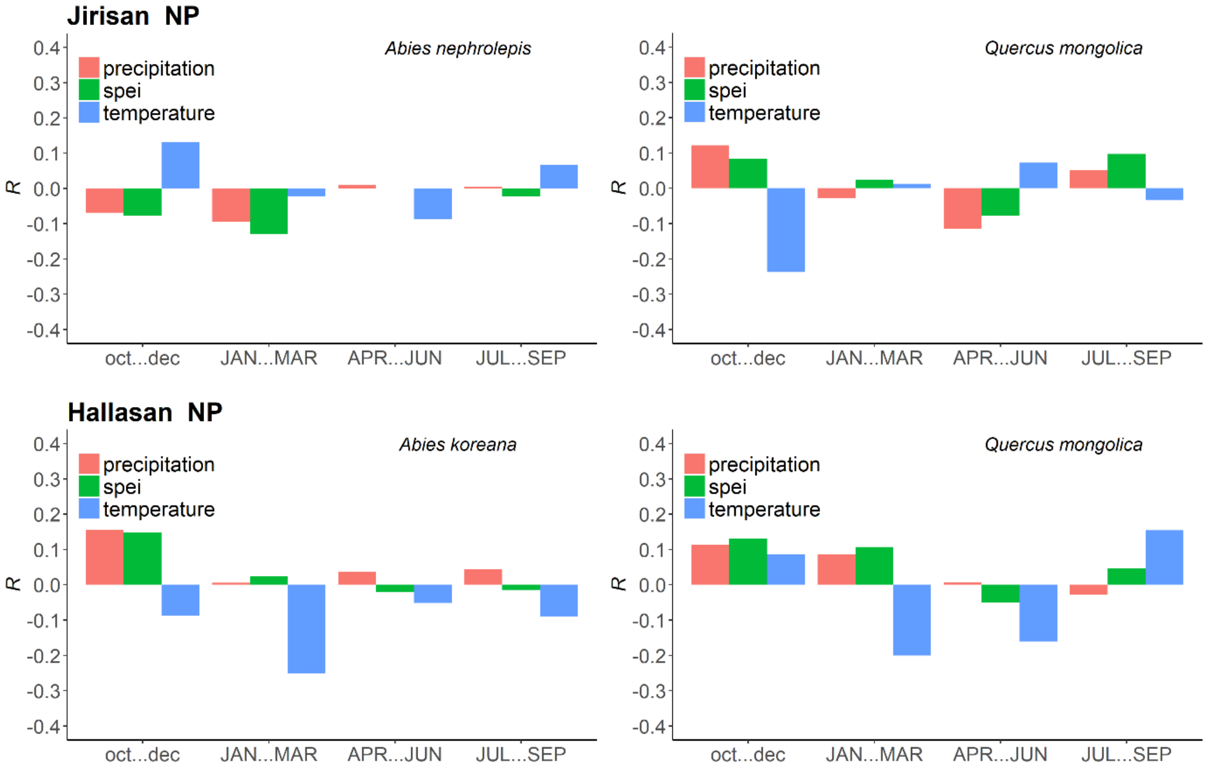


Fig. S3 Climate-growth relationships for the two most abundant species per locality. Two dominant species were selected as rare species with low sample replication are not suitable for the development of a robust chronology needed for reliable climate-growth relationship analysis. Pearson correlation coefficients (*R*) between tree-ring width chronologies and seasonal precipitation, temperature, and SPEI (standardised precipitation-evapotranspiration index) are shown, calculated over the period 1950-2004. Correlation coefficients were calculated for previous year autumn (October-December; oct…dec) to current year winter (January-March; JAN…MAR), spring (April-June; APR…JUN) and summer (July-September; JUL…SEP). Significant relationship (altogether three with $p < 0.05$) are marked with *. One should note that even the significant correlations are still relatively low with maximal correlation coefficient -0.27 in the case of Kerdovaya pad NR for relationship between *Quercus mongolica* chronology and temperature. Climatic data were gained from KNMI climate explorer (http://climexp.knmi.nl/).

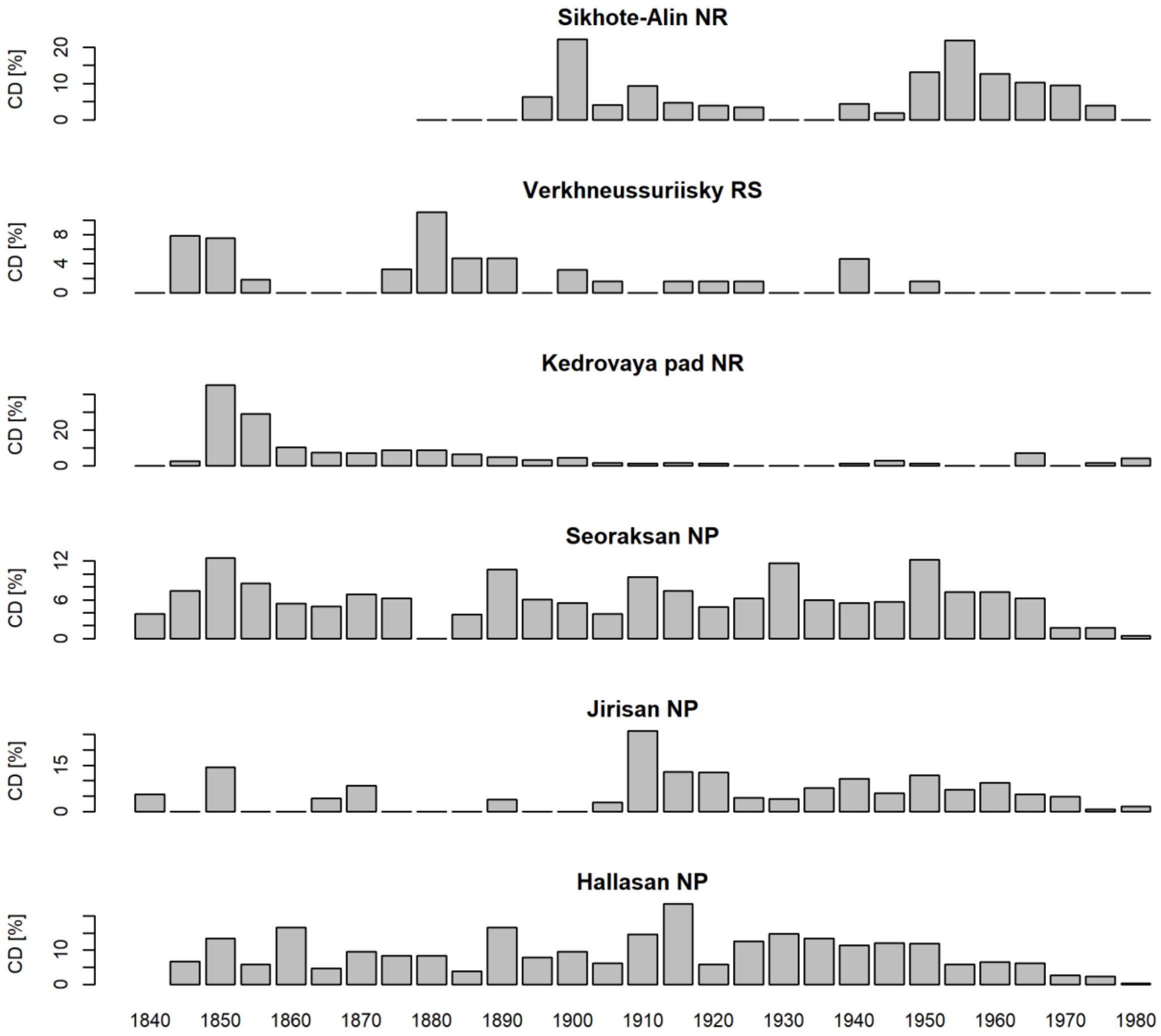


Fig. S4 Canopy disturbance chronologies for individual localities (see Table S4 for details about localities) showing the percentage of trees with release at 5-year intervals (see Table S5 for correlations between individual chronologies). CD is canopy disturbance derived from growth release analysis. Sites are sorted from south (bottom panel) to north (top panel).

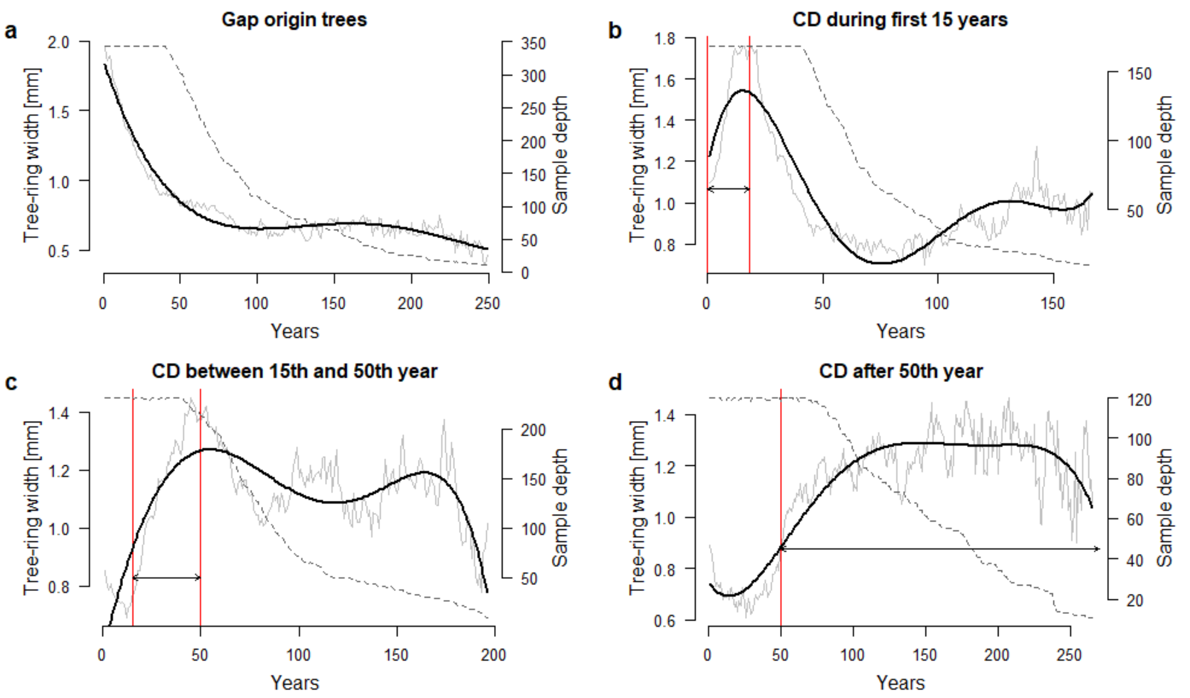


Fig. S5. Average growth trends (thick black curves) over all trees and sites divided to categories according the length of period preceding canopy disturbance. First group is represented by trees experiencing canopy disturbance (CD) at the early stage of their life and include trees with rapid early growth followed by a long and gradual decline (gap origin trees) (**a**) and trees with canopy disturbance during their first 15 years (**b**). To the second group belong trees with canopy disturbance after their 15th and before their 50th year (**c**) and the last group is represented by trees with canopy disturbance after their 50th year (**d**). To allow the presentation of the overall growth trends of various species with disturbance occurring in various calendar years, trees are ordered according the relative dates (with first measured ring at year 1) to highlight general pattern of occurrence of canopy disturbances. Grey lines show mean raw tree-ring width series of trees belonging to individual groups, dashed lines show the sample depth (here we truncated chronologies when sample size dropped below 10 trees per group), vertical red lines and arrows delimit the period of detected canopy disturbances for individual groups (the period is not marked for trees with gap origin as it is occurring during very first years of growth). For examples of individual growth series see Fig. S6.

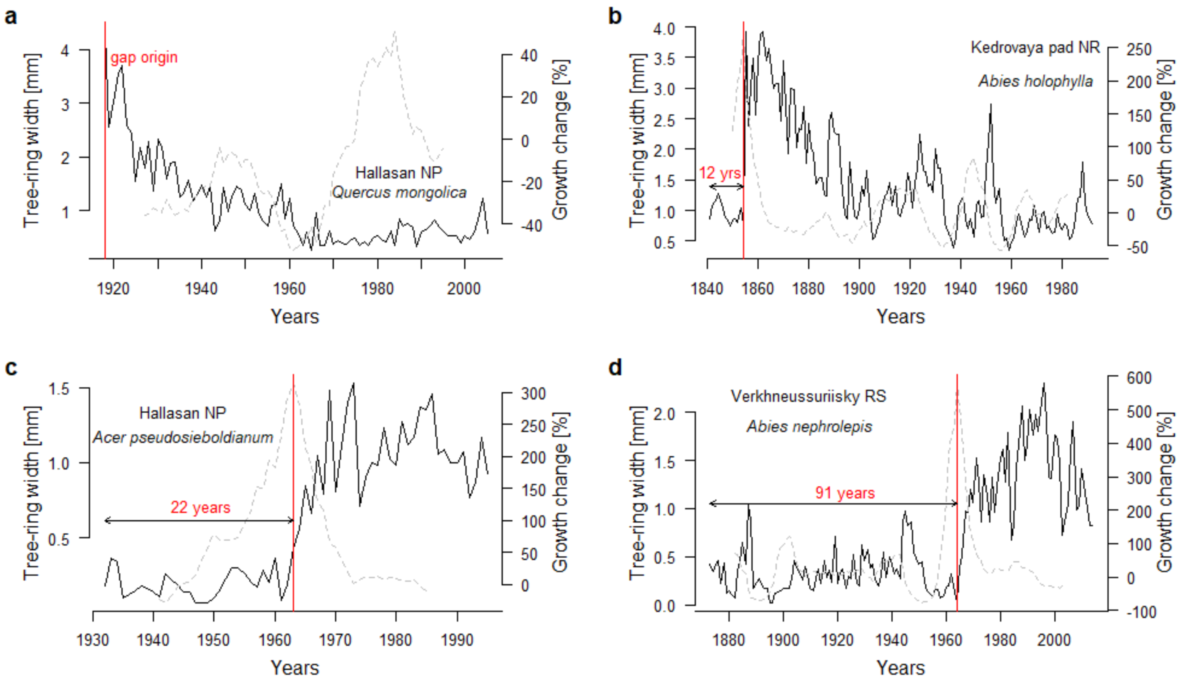


Fig. S6. Examples of individual growth series representing categories according the length of period preceding canopy disturbance. Trees experiencing canopy disturbance at the early stage of their life with rapid early growth followed by a long and gradual decline (gap origin trees) (**a**) were for the purpose of this paper grouped with trees with canopy disturbance during their first 15 years (**b**). Trees with canopy disturbance after their 15th and before their 50th year (**c**), and trees with canopy disturbance after their 50th year (**d**). Black lines show raw tree-ring width series for individual trees, dashed grey lines represent percentage growth change (59), vertical red lines mark the detected year of canopy disturbance, arrows indicate the length of the period preceding the disturbance (the precise number of years is written in red above the arrow) and locality and species (in italic) for selected individuals are displayed.

Supporting Tables

Table S1. Relationship between canopy disturbance chronologies (5-year intervals) for individual localities (see Table S4 for details about localities) and maximum wind speed during TCs for 5-year intervals. *R* = Pearson correlation coefficient. Not all relationships are significant (although at least very close to marginal significance) despite the high correlation coefficients, which is induced by a) short TCs data (starting 1945) and b) 5-year resolution of disturbance chronologies, limiting the pairs of degree of freedom for calculation of correlations. *p* = significance level of individual correlations. TC maximum wind speed data were gained from KNMI climate explorer (http://climexp.knmi.nl/).

	max. wind TC	
	R	*p*
Hallasan NP	0.82	0.01
Jirisan NP	0.53	0.11
Seoraksan NP	0.58	0.09
Kedrovaya pad NR	0.48	0.11
Verkhneussuriisky RS	0.93	0.01
Sikhote-Alin NR	0.79	0.02

Table S2. Relationship between latitude and the proportion of trees in individual groups according to the length of period preceding canopy disturbance (CD) reflecting TC activity. Results are shown for whole dataset and two time periods, trees established before (P1) and after (P2) 1920. Coefficients from generalized linear mixed-effect models (binomial family, logit link) with latitude and time-period as interacting fixed effect and localities as random effects are shown. Latitude was centered, therefore intercept refers to latitude of ~39.1° N. P2-P1 coefficients represent changes between time periods. Significance of intercept and latitudinal trend (= slope of linear mixed-effect models) and their change between time periods is indicated using significance codes: *n.s.*: non-significant; (*): $p < 0.1$; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

	Whole dataset				Before 1920 (P1)				After 1920 (P2)				P2 - P1			
	Intercept	*p*	*Latitudinal trend*	*p*	*Intercept*	*p*	*Latitudinal trend*	*p*	*Intercept*	*p*	*Latitudinal trend*	*p*	*Intercept*	*p*	*Latitudinal trend*	*p*
CD within first 15 yr	-0.331	***	-0.206	***	-0.255	**	-0.228	***	-0.348	***	-0.191	***	-0.093	*n.s.*	0.036	*n.s.*
CD between 15-50 yr	-1.171	***	0.142	***	-1.407	***	0.066	*	-0.811	***	0.233	***	0.596	***	0.166	***
CD after 50 yr	-2.253	***	0.242	***	-1.737	***	0.263	***	-3.756	***	0.145	*	-2.020	***	-0.118	(*)

Table S3. The relationship between latitude and the proportion of trees in individual groups according the length of period preceding canopy disturbance (CD) for four abundant species. Significance of intercept and latitudinal trend (= slope of linear mixed-effect models) is indicated using significance codes (*p*): *n.s.*: non-significant; (*): $p < 0.1$; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

	CD within first 15 yr				CD between 15-50 yr				CD after 50 yr			
	Intercept	*p*	*Latitudinal trend*	*p*	*Intercept*	*p*	*Latitudinal trend*	*p*	*Intercept*	*p*	*Latitudinal trend*	*p*
Abies nephrolepis	-0.517	**	-0.221	***	-0.481	**	0.12496	**	-2.415	***	0.20364	**
Pinus koraiensis	-0.168	*n.s.*	-0.276	***	-1.545	***	0.12885	(*)	-1.382	***	0.14498	*
Quercus mongolica	0.531	**	-0.0754	(*)	-1.588	***	0.0846	*n.s.*	-2.973	***	0.21988	*
Acer pseudosieboldianum	-1.024	*	-0.326	**	-0.882	*n.s.*	0.4027	*	-1.221	(*)	0.5615	*

Table S4. Basic characteristics for individual localities and the part of tree-ring network meeting all above described criteria. NP = national park, NR = nature reserve, RS = research station.

locality number	locality name	latitude N	longitude E	number of trees	mean age	oldest tree	CD < 15 yrs	CD 15-50 yrs	CD > 50 yrs	no CD
1	Hallasan NP	33°22'	126°35'	303	74	236	212	30	3	58
2	Jirisan NP	35°20'	127°40'	158	87	195	98	26	7	27
3	Seoraksan NP	38°10'	128°20'	313	97	351	144	80	27	62
4	Kedrovaya pad NR	43°10'	131°30'	117	160	242	30	39	23	25
5	Verkhneussuriisky RS	44°10'	134°10'	126	199	384	23	23	65	15
6	Sikhote-Alin NR	45°10'	135°50'	190	86	332	35	99	31	25

Table S5. Relationship between canopy disturbance chronologies for individual localities. Pearson correlation coefficients are shown, in case that relationship was significant, one of the following significance codes is behind correlation coefficient: (*): $p < 0.1$; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

	Hallasan NP	Jirisan NP	Seoraksan NP	Kedrovaya pad NR	Verkhneussuriisky RS	Sikhote-Alin NR
Hallasan NP	×	0.41*	0.58**	0.04	0.07	-0.12
Jirisan NP	0.41*	×	0.38*	-0.06	0.08	0.17
Seoraksan NP	0.58**	0.38*	×	0.27	0.30*	0.22
Kedrovaya pad NR	0.04	-0.06	0.27	×	0.34(*)	-0.19
Verkhneussuriisky RS	0.07	0.08	0.30*	0.34(*)	×	-0.25
Sikhote-Alin NR	-0.12	0.17	0.22	-0.19	-0.25	×

References for SI reference citations

75. Nehrbass-Ahles C, *et al.* (2014) The influence of sampling design on tree-ring-based quantification of forest growth. *Glob Change Biol* 20(9):2867-2885.

76. Gartner H & Nievergelt D (2010) The core-microtome: A new tool for surface preparation on cores and time series analysis of varying cell parameters. *Dendrochronologia* 28(2):85-92.

77. Yamaguchi DK (1991) A Simple Method for Cross-Dating Increment Cores from Living Trees. *Can J Forest Res* 21(3):414-416.

78. Eckstein D & Bauch J (1969) Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. *Forstwiss Centralbl* 88(1):230-250.

79. Baillie MGL & Pilcher JR (1973) A simple crossdating program for tree-ring research. *Tree-ring Bull* 1973(33):7-14.

80. Altman J, Dolezal J, & Cizek L (2016) Age estimation of large trees: New method based on partial increment core tested on an example of veteran oaks. *For Ecol Manage* 380:82-89.

81. Druckenbrod DL (2005) Dendroecological reconstructions of forest disturbance history using time-series analysis with intervention detection. *Can J Forest Res* 35(4):868-876.

82. Fraver S & White AS (2005) Identifying growth releases in dendrochronological studies of forest disturbance. *Can J Forest Res* 35(7):1648-1656.

83. Rubino DL & McCarthy BC (2004) Comparative analysis of dendroecological methods used to assess disturbance events. *Dendrochronologia* 21(3):97-115.

84. Black BA, Abrams MD, Rentch JS, & Gould PJ (2009) Properties of boundary-line release criteria in North American tree species. *Ann For Sci* 66(2):205.

85. Black BA, *et al.* (2004) Development and application of boundary-line release criteria. *Dendrochronologia* 22(1):31-42.

86. NOAA (2018) Contributors of the International Tree-Ring Data Bank, IGBP PAGES/World Data Center for Paleoclimatology, NOAA/NGDC Paleoclimatology Program. (Boulder, Colorado, USA). Avaliable online at https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring

87. Zielonka T, Holeksa J, Fleischer P, & Kapusta P (2010) A tree-ring reconstruction of wind disturbances in a forest of the Slovakian Tatra Mountains, Western Carpathians. *J Veg Sci* 21(1):31-42.

88. Ziaco E, Biondi F, Di Filippo A, & Piovesan G (2012) Biogeoclimatic influences on tree growth releases identified by the boundary line method in beech (Fagus sylvatica L.) populations of southern Europe. *For Ecol Manage* 286:28-37.

89. Nagel T, Levanic T, & Diaci J (2007) A dendroecological reconstruction of disturbance in an old-growth *Fagus-Abies* forest in Slovenia. *Ann For Sci* 64(8):891-897.

90. Samonil P, Antolik L, Svoboda M, & Adam D (2009) Dynamics of windthrow events in a natural fir-beech forest in the Carpathian mountains. *For Ecol Manage* 257(3):1148-1156.

91. Lorimer CG, Frelich LE, & Nordheim EV (1988) Estimating gap origin probabilities for canopy trees. *Ecology* 69(3):778-785.

92. Rentch JS, Fajvan MA, & Hicks RR (2003) Oak establishment and canopy accession strategies in five old-growth stands in the central hardwood forest region. *For Ecol Manage* 184(1-3):285-297.

93. Berg EE, Henry JD, Fastie CL, De Volder AD, & Matsuoka SM (2006) Spruce beetle outbreaks on the Kenai Peninsula, Alaska, and Kluane National Park and Reserve,

Yukon Territory: Relationship to summer temperatures and regional differences in disturbance regimes. *For Ecol Manage* 227(3):219-232.

94. Butler DR & Sawyer CF (2008) Dendrogeomorphology and high-magnitude snow avalanches: a review and case study. *Nat Hazard Earth Sys* 8(2):303-309.

95. Cada V, Svoboda M, & Janda P (2013) Dendrochronological reconstruction of the disturbance history and past development of the mountain Norway spruce in the Bohemian Forest, central Europe. *For Ecol Manage* 295:59-68.

96. Cada V, *et al.* (2016) Frequent severe natural disturbances and non-equilibrium landscape dynamics shaped the mountain spruce forest in central Europe. *For Ecol Manage* 363:169-178.

97. Svoboda M, *et al.* (2014) Landscape-level variability in historical disturbance in primary *Picea abies* mountain forests of the Eastern Carpathians, Romania. *J Veg Sci* 25(2):386-401.