Increased stem density and competition diminishes potential positive effects of warming at alpine treeline

Yafeng Wang[1], Neil Pederson[2], Aaron M. Ellison[2*], Hannah Buckley[2,3], Bradley Case[2,4], Eryuan Liang[1,5*], J. Julio Camarero[6]

Appendix A

Field sampling

Smith fir was the only tree species in each plot that reached canopy status. Soils in the plots were slightly acidic (pH = 5-6), and understory vegetation was a mix of mosses and lichens (≈ 60% cover). A few herbaceous plants (e.g., *Rubus thibetanus*, *Bergenia purpurascens*) were found in treeline ecotone, but they accounted for < 3% of the ground cover. Fir seedlings establish atop these and in organic matter (Wang et al. 2012).

At each of the two sites, we established a square 150 ×150-m plot in a topographically uniform area parallel to the local slope. Note that the plot at site N1 was an extension of the 30 × 150-m N1 plot previously studied by Liang et al. (2011). The upper portion of each plot encompassed the current treeline. The relative origin for each plot (x, y = 0, 0) was located at the lower left corner of the plot facing upslope (see Camarero and Gutiérrez 2004). The upper left part of the N1 site was occupied by dense *Rhododendron* dense thickets, and that is the reason why this portion of the plot was excluded from our analyses.

Every tree within each plot was mapped and measured in early November 2011 (N1) and June 2014 (N2) following the previous field sampling protocol used by Liang et al. (2011). Diameter at breast height (DBH) measured at 1.3 m above ground and the horizontal diameters of the canopy parallel to the x and y axes of the plot were measured. If the height of an individual tree was < 2 m, we measured its height with a tape. Otherwise tree height was determined using a clinometer (± 0.25 m). A total of 2053 (for N1) and 3057 (N2) trees were sampled and mapped, but only six dead individuals were found.

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Appendix B

Point-pattern analyses

Univariate point pattern analyses

The univariate $O_{11}(r)$ statistic as implemented in the Programita software package (Wiegand and Moloney 2014) was used to characterize the spatial patterns of the three different age classes (adults, juveniles, and seedlings). We used a heterogeneous Poisson process as a null model for complete spatial randomness (CSR), and calculated simulation envelopes to determine if the observed pattern of each age class was random, clumped, or regularly spaced. A 99% simulation envelope of $O_{11}(r)$ was constructed from 999 Monte Carlo simulations. If the observed$O_{11}(r)$ was above or below the simulation envelopes, the pattern was considered to be significantly aggregated or hyperdispersed (regular), respectively, at a particular spatial scale. Since spatial relationships for Smith fir treeline populations previously had been detected at scales of 1-7 m (Wang et al. 2012), we estimated $O_{11}(r)$ at a spatial resolution of 1 m and tested for departure from CSR for scales from 1 to 15 m. Finally, because simulation envelope tests were calculated at multiple spatial scales, the Type I error rate can be inflated (Wiegand and Moloney 2014). Therefore, we also applied a Goodness-of-Fit (GoF) test to collapse that scale-dependent information into a single test statistic for formal hypothesis testing.

Bivariate point pattern analyses

We used the bivariate $O_{12}(r)$ statistic as implemented in the Programita software package (Wiegand and Moloney 2014) to characterize the spatial associations between the three age classes. We assumed that adults or juveniles impact juveniles and seedlings, respectively, but not vice versa. Hence, we used an antecedent condition as the null model, and only randomized the locations of either juveniles or seedlings while keeping the locations of adults or juveniles, respectively, fixed (Wiegand and Moloney 2014). As in the univariate case, if the O_{12} (r) statistic was above or below the boundaries of a 99% simulation envelopes, the pattern was considered to show significant positive (attraction) or negative (repulsion) associations, respectively, at a given spatial scale. Again, we used a 1-m resolution and tested for CSR at scales from 1-15 m, and applied a GoF test to minimize Type I error rates.

Mark correlation function: bivariate patterns with two quantitative marks

To detect if competition affected recent regeneration, we compared the locations and heights of adults and juveniles with the densities of individuals recruited during the last 30 years at a radius of 5, 10 and 15 m from each focal tree. We calculated the density of seedlings found around either adults or juveniles by using the spatstat package (Baddeley and Turner 2013) within the R statistical software, version 3.0.1 (R Development Core Team 2015). Similar to our prior analysis, we performed a bivariate mark correlation analysis by calculating the spatial relationship between height and recruitment density in the tree neighborhood using the Programita software. In this case, we used two additional bivariate mark-correlation functions to identify the spatial pattern of tree height (first *r*-mark correlation function $k_{m1.}$ (r)) while highlighting the relationships between height and recruitment patterns (Moran's *I*-type summary statistic $I_{m1m2}(r)$; see Wiegand and Moloney 2014).

References

Baddeley, A. J., and Turner, R. 2013. Package 'Spatstat': Spatial Point Pattern analysis. http://mirrors.ustc.edu.cn/CRAN/.

R Development Core Team. 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.r-project.org/.

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Appendix C

TABLE C1. Statistical parameters summarizing the univariate and bivariate point pattern analyses of Smith fir individuals (adults, juveniles and seedlings) growing in two treeline sites. The analyses were calculated for five 30-year long periods (see also Fig. 1). Displayed statistics are: nn, mean distance to the nearest neighbor; λ, intensity or density of the pattern within an area delimited by a convex hull; GoF, Goodness-of-Fit test calculated for each point-pattern analysis (considering the analyzed distance interval from 1 to 15 m) with its corresponding significance level (*P*). Significant ($P < 0.05$) GoF values are in bold. The first two statistics were calculated only for the univariate case.

Site	Spatial pattern analysis of tree individuals		Periods 1862-1891			1892-1921			1922-1951			1952-1981			1982-2011/2013		
			nn (m)	λ (ind ha^{-1})	GoF (*P*)	nn (m)	λ (ind ha^{-1})	GoF (*P*)	nn (m)	λ (ind ha^{-1})	GoF (*P*)	nn (m)	λ (ind ha^{-1})	GoF (*P*)	nn (m)	λ (ind ha^{-1})	GoF (*P*)
N1	Univariate analyses	Adults	11.1	28	690 (0.31)	8.3	43	660 (0.34)	7.4	50	475 (0.52)	5.9	60	190 (0.81)	5.2	85	400 (0.60)
		Juveniles	7.8	36	90 (0.91)	7.8	40	670 (0.33)	6.5	49	450 (0.55)	4.1	117	**985** (0.02)	1.7	450	**995** (0.005)
		Seedlings	9.0	31	915 (0.09)	9.2	41	635 (0.37)	5.2	80	**980** (0.02)	1.7	389	**990** (0.01)	1.3	687	**995** (0.005)
N2		Adults	12.9	17	708 (0.29)	8.6	33	715 (0.28)	7.1	47	541 (0.86)	6.3	64	390 (0.61)	5.2	97	506 (0.49)
		Juveniles	8.3	32	284 (0.72)	7.9	37	66 (0.93)	6.1	60	914 (0.08)	4.6	75	**999** (0.002)	2.3	210	**1000** (0.001)

		Seedlings	11.2	20	564 (0.44)	7.5	37	**982** (0.019)	6.3	31	**999** (0.002)	3.2	130	**1000** (0.001)	1.0	1048	**1000** (0.001)
N1	Bivariate analyses	Adults - juveniles	———		35 (0.96)	———		435 (0.56)	———		680 (0.32)	———		**990** (0.01)	———		**990** (0.01)
		Adults - seedlings	———		760 (0.24)	———		580 (0.42)	———		**980** (0.02)	———		**995** (0.005)	———		**995** (0.005)
		Juveniles - seedlings	———		590 (0.41)	———		545 (0.45)	———		510 (0.49)	———		**985** (0.02)	———		**998** (0.001)
N2		Adults - juveniles	———		621 (0.38)	———		102 (0.89)	———		924 (0.07)	———		**984** (0.017)	———		**983** (0.018)
		Adults - seedlings	———		115 (0.88)	———		919 (0.08)	———		906 (0.09)	———		**1000** (0.001)	———		**1000** (0.001)
		Juveniles -seedlings	———		281(0.97)	———		113 (0.88)	———		148 (0.85)	———		**1000** (0.001)	———		**1000** (0.001)

TABLE C2. Pearson correlation coefficients obtained by relating recruitment data or recruitment residuals (obtained after fitting negative exponential curves to recruitment data) with reconstructed summer mean minimum and winter half-year mean temperatures for the Tibetan Plateau (period 1760-2000, see Fig. 3). Temperatures were averaged considering four different time periods (10, 20, 30 and 40 years). The different *P* values are indicated by different symbols (one, two and three asterisks correspond to $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively).

Site	Period of temperature average in years (No. periods)	Summer temperature		Winter temperature	
		Recruitment data	Recruitment residuals	Recruitment data	Recruitment residuals
N1	10 (24)	0.740***	0.737***	0.716***	0.713
	20 (12)	0.729*	0.760*	0.784*	0.781*
	30 (8)	0.668	0.829*	0.619	0.810*
	40 (6)	0.861*	0.775	0.785	0.781
N2	10 (24)	0.674***	0.268	0.719***	0.244
	20 (12)	0.773*	0.509	0.701	0.256
	30 (8)	0.629	0.297	0.611	0.158
	40 (6)	0.743*	0.673*	0.771	0.478

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Appendix D

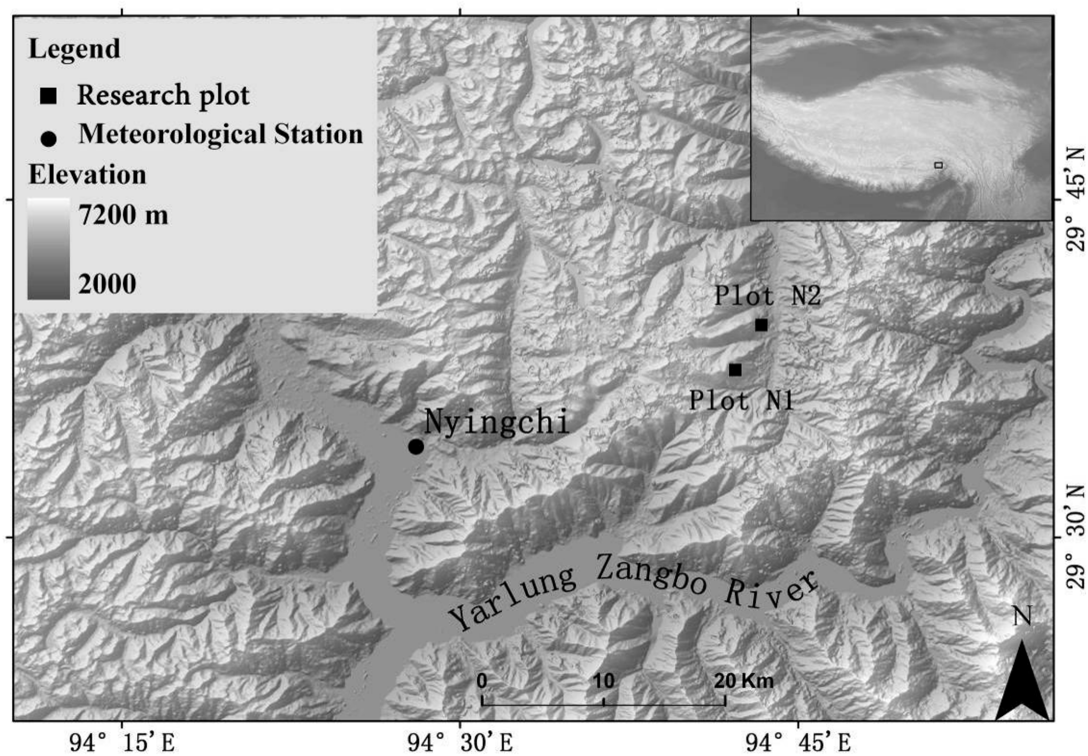

FIG. D1. Map showing the locations of the studied Smith fir treeline sites situated in the Sygera Mountains, southeast Tibetan Plateau, eastern Asia (see upper inset) and the Nyingchi meteorological station located at 3,000 m a.s.l. The upper limits of N1 and N2 sites are 4390 and 4370 m a.s.l., respectively.

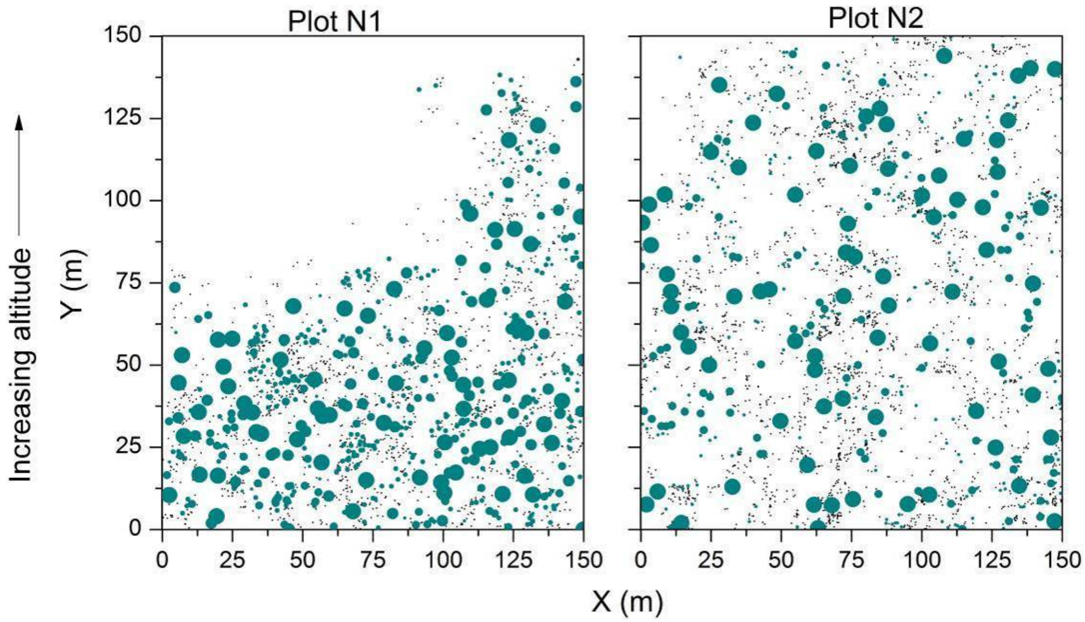

FIG. D2. Spatial positions of mapped Smith fir individuals located within the study treeline plots located at N1 (n = 2053) and N2 (n = 3057) sites. The color circles show trees and their size is proportional to their diameters at breast height ($DBH^{0.5}$). The small points show individuals which were recruited during the last 30 years. Increasing altitude corresponds to higher values along the *y* axis. Note that dense patches of tall *Rhododendron* individuals dominate above the treeline in the upper left area of N1 site.

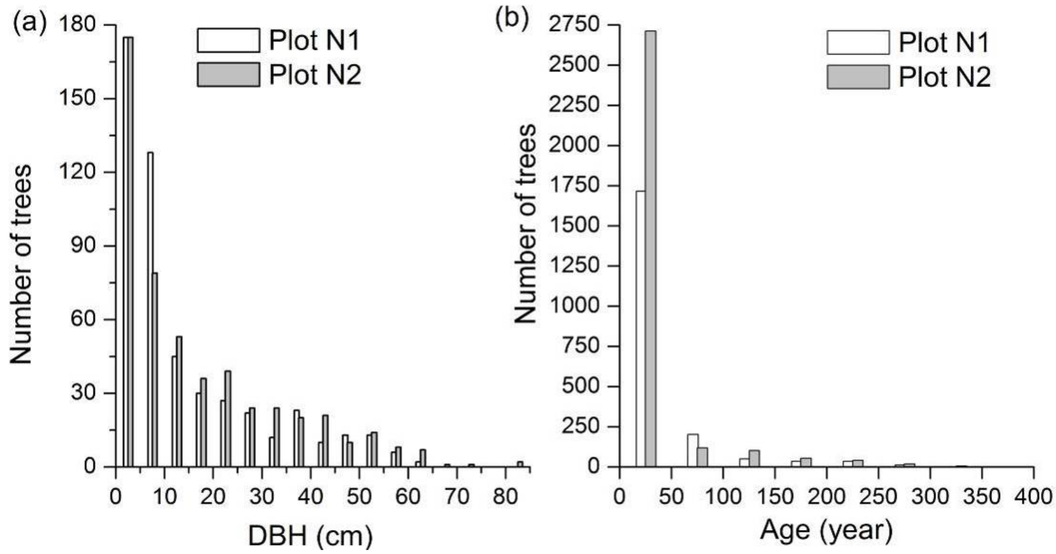

FIG. D3. Distribution of sampled trees according to their diameter at breast height (DBH, a) and age (b) in the study treelines (white bars and gray bars correspond to N1 and N2 sites).

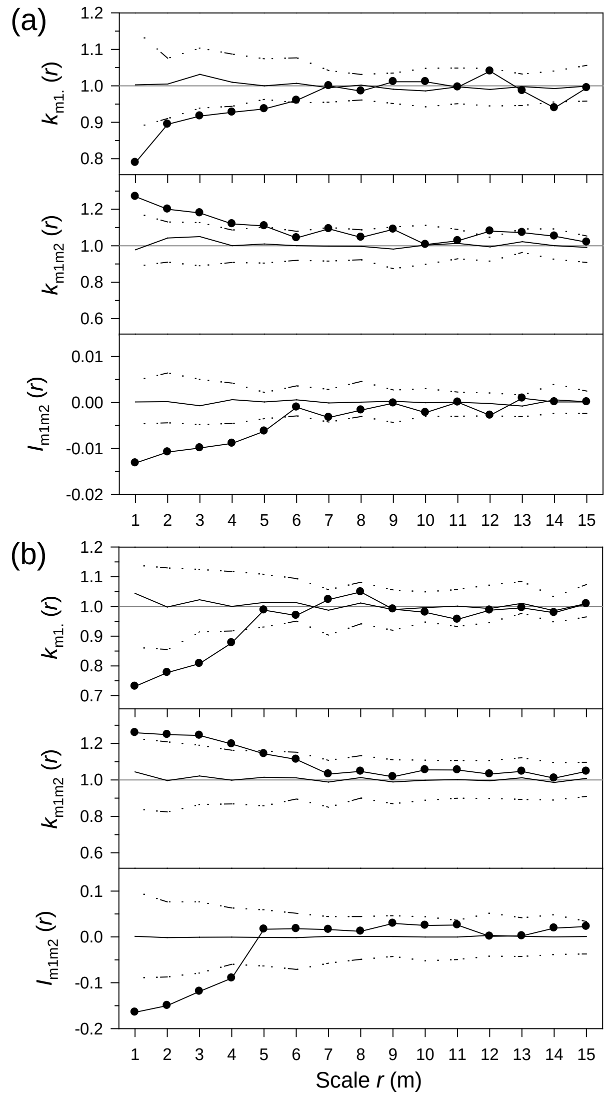

FIG. D4. Bivariate mark correlation functions ($k_{m1.}$ (r), $k_{m1m2}(r)$, $I_{m1m2}(r)$; upper figures) plotted as a function of scale (r) and based on the spatial patterns of tree height and the density of recruits in N1 (a) and N2 (b) treeline sites. Recruitment density corresponds to seedlings germinated during the last 30 years and found at a radius of 15 m from each target tree.