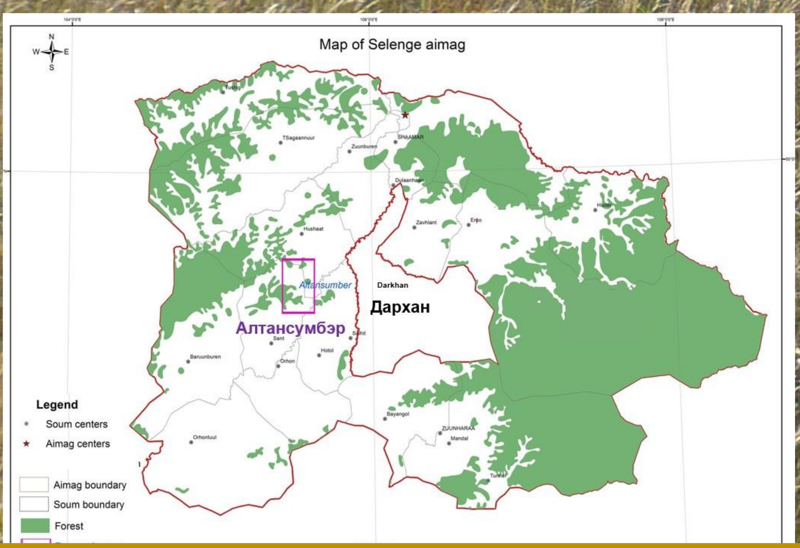
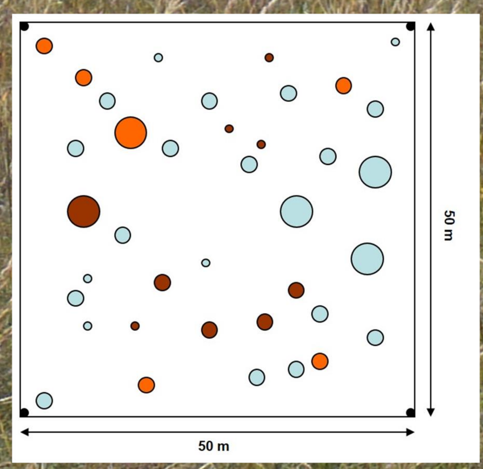
Stand characteristics and effects of thinning on tree growth and spatial positioning in the larch and birch forests of Altansumber

The development of ecological adapted silviculture and forest management is intensively discussed in Mongolia. Reliable data from experimental thinning trials are hardly available. Thinnings can have various effects on the stand level and single tree level, such as triggering growth, improve or lower stability against certain disturbances or change microclimate in soil. Our contribution focuses on the effects of thinning on growth and stand structure on the two most common tree species of the Mongolian mountain forest steppe. Larch (Larix sibirica Ledeb.) is the most important tree species in economic terms. Birch (Betula platyphylla Sukaczev) is of special ecological importance, especially on succession sites. Silvicultural management of larch and birch generally requires early and intensive thinning in order to ensure good crown development, which is needed for good yield and good timber quality. In 2009 we established thinning trials during an UNFAO project (GCP/MON/002/NET) with the forest user group (FUG) Altansumber for studying the response of larch and birch to selective cutting. Overall 19 plots were established. Twelve plots belong to thinning trials: B I (pure birch stands, 3 plots), B II (pure birch stands, 3 plots); L I (pure larch, 3 plots); L II (pure larch, 3 plots).

«ALTANSUMBER» PARTICIPATORY ESTABLISHMENT OF THINNING TRIALS



Map from forest user group Altansumber (FAO Darchan office 2009)



Example of plot design (circles refer to different trees)

During thinning in a larch stand: supported by the FUG.

Reference Stand	Main Tree Species	Height above Sea Level	Expo-sition	N (Plots)	Plot Size (m^2) 2009	Indication of Disturbances	Year of first assess-ment
BI *	birch	934	N	3	2500 (1550)	s.f.	2009
BII	birch	966	N	3	2500	s.f.	2009
LI	larch	911	NW	3	2500	s.f.	2009
LII	larch	976	NW	3	2500	s.f., s.p.l.	2009

STAND MEASURES DIRECTLY BEFORE AND AFTER THINNING AND THREE YEARS LATER (Gradel et al. 2017_3)

Stand measures of the plots before (2009_{before}), after the thinning (2009_{after}) and at the end of the observation period in 2012. N/ha = stem number per hectare; BA/ha=basal area per hectare; dom. height (m) = dominant height; CV: diameter coefficient of variation; Dg: quadratic mean diameter of all trees: D: arithmetic mean diameter of all trees; Dg_200: quadratic mean diameter of the 200 strongest trees; D_200: arithmetic mean diameter of the 200 strongest trees; m. int. = medium intensity treatment; low int. = low intensity treatment; unth. = no treatment (unthinned).

Stem number and Dg on some plots indicated that the increase in basal area in the years after thinning was due only to the growth response of the remaining trees (*LII medium intensity treatment, BII low intensity treatment*), whereas on other plots the increase was also due to ingrowth of young trees (e.g., *BI medium intensity treatment, LII low intensity treatment*). Over the course of the observations, the Dg changed more strongly on the thinned plots than on the unthinned plots. The actual thinning effect becomes clearer when focusing on the strongest trees only. The mean diameters of the top 200 larch trees per ha remained nearly unchanged after the tree removals. In contrast, for birch, a slight reduction in mean diameter of the top 200 trees was observed indicating that some of the larger trees were harvested. The diameter coefficient of variation (CV or DBH-differentiation according to von Gadow and Hui (2002), respectively) on the plots did change only little. However, on all plots of the II-series, the CV decreased slightly in response to thinning.

BIRCH { B I: stand age in 2012: 44; B II: stand age in 2012: 68

Stand	Plot	2009_{before}	2009_{after}	2012
N/ha				
BI	m. int.	1144	568	736
	low int.	1174	961	1045
	unth.	1368	unth.	1510
BII	m. int.	984	484	500
	low int.	1136	808	796
	unth.	1188	unth.	1192
BA (m^2)/ha				
BI	m. int.	14.659	6.974	8.567
	low int.	8.690	6.988	8.746
	unth.	10.841	unth.	12.223
BII	m. int.	17.289	10.791	11.366
	low int.	17.387	13.359	14.310
	unth.	17.895	unth.	19.249
dom. height (m)				
BI	m. int.	12.3	11.8	11.9
	low int.	10.2	10.3	10.7
	unth.	11.0	unth.	11.6
BII	m. int.	14.9	14.8	15.0
	low int.	14.4	14.4	14.6
	unth.	14.5	unth.	14.7
CV				
BI	m. int.	0.424	0.426	0.416
	low int.	0.251	0.246	0.251
	unth.	0.352	unth.	0.329
BII	m. int.	0.333	0.279	0.286
	low int.	0.276	0.263	0.263
	unth.	0.278	unth.	0.232
D				
BI	m. int.	11.8	11.5	11.2
	low int.	9.4	9.3	10.0
	unth.	9.5	unth.	9.7
BII	m. int.	14.0	16.0	16.4
	low int.	13.4	14.0	14.6
	unth.	13.3	unth.	13.8
Dg				
BI	m. int.	12.8	12.4	12.2
	low int.	9.7	9.6	10.3
	unth.	10.0	unth.	10.2
BII	m. int.	15.0	16.8	17.0
	low int.	13.9	14.5	15.1
	unth.	13.8	unth.	14.3
D_200				
BI	m. int.	21.1	16.8	17.7
	low int.	13.4	12.7	14.0
	unth.	16.1	unth.	16.3
BII	m. int.	21.0	20.3	21.0
	low int.	19.4	19.0	19.8
	unth.	19.4	unth.	20.2
Dg_200				
BI	m. int.	21.3	17.4	18.2
	low int.	13.7	13.0	14.3
	unth.	16.6	unth.	16.8
BII	m. int.	21.4	20.4	21.2
	low int.	19.5	19.1	19.9
	unth.	19.5	unth.	20.3

LARCH { L I: stand age in 2012: 22; L II: stand age in 2012: 61

Stand	Plot	2009_{before}	2009_{after}	2012
N/ha				
LI	m. int.	1528	776	868
	low int.	1504	1148	1268
	unth.	1136	unth.	1200
LII	m. int.	656	524	524
	low int.	624	564	624
	unth.	416	unth.	420
BA (m^2)/ha				
LI	m. int.	16.707	11.039	14.404
	low int.	13.513	11.320	15.165
	unth.	15.657	unth.	18.749
LII	m. int.	24.878	22.026	23.692
	low int.	23.025	21.786	23.025
	unth.	21.635	unth.	23.154
dom. height (m)				
LI	m. int.	12.1	12.0	12.6
	low int.	11.4	11.4	12.0
	unth.	12.8	unth.	13.1
LII	m. int.	16.4	16.4	16.5
	low int.	16.0	16.0	16.0
	unth.	16.5	unth.	16.7
CV				
LI	m. int.	0.359	0.373	0.364
	low int.	0.311	0.316	0.310
	unth.	0.473	unth.	0.449
LII	m. int.	0.362	0.342	0.340
	low int.	0.269	0.260	0.267
	unth.	0.249	unth.	0.252
D				
LI	m. int.	11.1	12.6	13.7
	low int.	10.2	10.7	11.8
	unth.	12.0	unth.	12.9
LII	m. int.	20.7	21.9	22.7
	low int.	20.8	21.5	20.9
	unth.	24.9	unth.	30.9
Dg				
LI	m. int.	11.8	13.5	14.5
	low int.	10.7	11.2	12.4
	unth.	13.2	unth.	14.1
LII	m. int.	22.0	23.1	24.0
	low int.	21.7	22.2	22.0
	unth.	25.7	unth.	26.5
D_200				
LI	m. int.	18.0	17.9	20.0
	low int.	15.6	15.6	17.5
	unth.	20.3	unth.	21.8
LII	m. int.	28.9	28.7	29.8
	low int.	22.2	22.6	28.4
	unth.	30.0	unth.	30.9
Dg_200				
LI	m. int.	19.0	18.9	20.8
	low int.	16.4	16.4	18.2
	unth.	22.1	unth.	23.4
LII	m. int.	29.5	29.3	30.4
	low int.	27.5	27.5	28.6
	unth.	30.2	unth.	31.1

HARVEST EVENT ANALYSIS (Gradel et al. 2015; Gradel et al. 2017_3)

Non-spatial harvest event analysis (Characterisation of Thinning Intensityand Type): We characterised the thinnings by thinning weight (rG ratio; (Murray & Gadow 1993) and thinning type (NG ratio) (Gadow et al.2012). Thinning weight reflects thinning intensity. The NG ratio indicates the thinning type, e.g., thinning from below or above. Values below one indicate thinning from above, values higher than one indicate thinning from below. A value near one indicates indifferent thinning (Vitikova et al. 2016), meaning that the proportion of removed stems was proportional to the removed basal area:

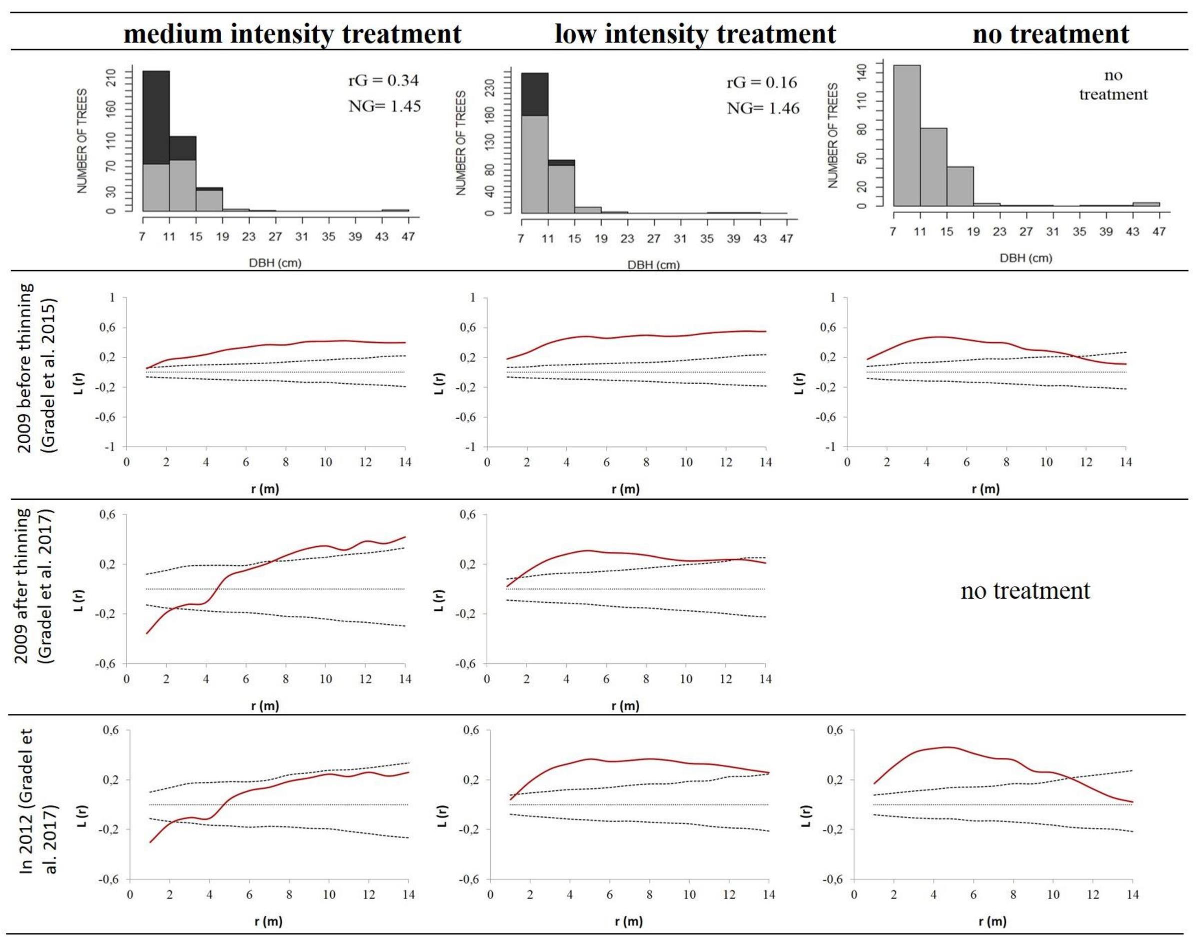
$$rG = \frac{G_{removed}(m^2/ha)}{G_{total}(m^2/ha)} \qquad NG = \frac{(N_{removed}/N_{total})}{G_{removed}/G_{total}}$$

where, N = stem number; G = basal area

Assessment of spatial tree distribution pattern was done by testing the hypothesis of complete spatial randomness (CSR), $L_{(r)}>0$ indicates aggregation of the pattern up to distance r, and $L_{(r)} < 0$ indicates regularity up to distance r (see Wiegand 2004):

$$L_{(r)} = \sqrt{\frac{K(r)}{\pi}} - r \qquad with\ L_{(r)} = 0\ for\ r \geq 0$$

Example: Larch stand LI



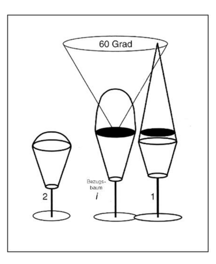
Example of diameter distributions and a non-spatial harvest event analysis (larch stand LI; grey: trees remaining after thinning; black: trees removed during the thinning): rG ratio indicates thinning intensity; NG ratio indicates the thining type: in both thinned plots thinning from below (NG >1)

Example of the analyses of the thinning on the spatial distribution pattern: The larch plots of the LI-series exhibited clumped tree distributions before harvest. The thinning intervention reduced clumping and resulted in a more uniform distribution. Some patterns shifted toward a significant regular distribution pattern at lower distances (e.g. L I medium intensity treatment). Three years after thinning, some of the plots had buffered some of the thinning effects by ingrowth of stems (not only larch, but also birch plots), developing away from the observed thinning event-induced regularity.

Evaluation of single tree growth response (Gradel et al. 2017_3)

A methodology for the assessment of the effects of thinning on the growth of single trees

1. Identify / select the competitors:
(option a) average nearest neighbor distance (NND) on each plot after thinning by 2 and round this to classes of meters: resulting values are competitor search radii (**NNDSR**) which ranged, depending on stem density, between 3 and 7 meters. (option b) we applied the cone-method suggested by Pretzsch (1995; 2002) using an inverted cone with an opening angle of 60° at 60% tree height. All neighboring trees that entered the cone of tree i were considered as competitors.



Cone method (Pretzsch 1995; 2002); implemented with excel and R-statistics (Gradel et al. 2017_4)

2. Select competition index:
We selected the distance weighted Hegyi-index for the description of completion (Hegyi 1974).

$$HgCI_i = \sum_{j=1}^{n} \frac{d_j}{d_i} \cdot \frac{1}{dist_{ij}}$$

where, d_i = diameter of tree i; d_j = diameter of competitor tree j; $dist_{ij}$= distance between tree i and tree j

3. Calculate the competition before and after the disturbance event (e.g. thinning):
We quantified the relative effect of a reduction in competition by calculating CI_{diff} (*absolute competition difference*: the difference between the Hegyi-index before and after thinning) and divided the result by the Heygi-index before thinning (CI_{rel}). CI_{rel} (*relative competition relief*) can reach values between 0 and 1. The higher the value, the greater the reduction in competition (Gradel et al. 2017_3).

$$CI_{rel} = \frac{HgCI_1 - HgCI_2}{HgCI_1}$$

where, $HgCI_1$ = Hegyi index of tree i before the thinning; $HgCI_2$= Hegyi index of tree i after the thinning

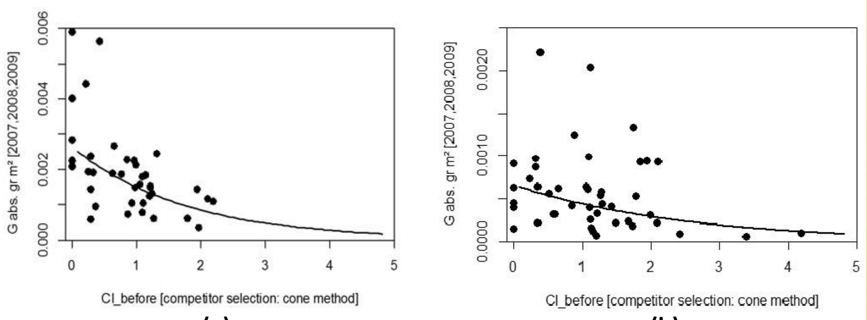
4. Calculate absolute and relative growth:
We defined absolute growth (*abs.gr*) as the sum of the annual basal area growth (based on wood cores: Gradel et al. 2017_1; 2017_2) of tree *i* after the thinning event (2010–2012). In order to quantify the relative change in basal growth of tree *i* (*rel.gr*), we divided *abs.gr* by the mean annual growth of basal area (derived from the stem cores and initial DBH-measurements) of the three years preceding the thinning event (2007–2009).

$$rel.gr = \frac{\overline{w}(period\ 2)}{\overline{w}(period\ 1)}$$

where, $\overline{w}_{(period\ 1)}$ = mean annual growth of basal area of tree i (2007–2009); $\overline{w}_{(period\ 2)}$ = mean annual growth of basal area of tree i (2010–2012); equivalent to *abs.gr*.

5. Put the variables as fixed effects into a linear mixed model (LMM) to describe and analyze absolute growth (*abs.gr*) and relative growth (*rel.gr*) after thinning:
We hypothesized that the *rel.gr* of larch and birch positively correlate to CI_{rel}. Each tree *i* in plot *j* of stand *k* represents a sample unit. To avoid pseudoreplication, we used a linear mixed model approach (LMM), which includes fixed effects (competition quantified by CI, DBH) and random effects (stand, plot) (Crawley 2007; Zuur et al. 2009). All models were optimized based on the restricted maximum likelihood method (REML) Zuur et al. 2009). We also tested for interactions between initial DBH and CI_{rel}.

Less competition before thinning means better growth



(a) Relationship between competition index (CI_before) and basal area growth (2007 to 2009) of larch prior to thinning: $R^2 = 0.3257$, $p < 0.05$.
(b) Relationship between competition index (CI_before) and basal area growth (2007 to 2009) of birch prior to thinning:: $R^2 = 0.1695$, $p < 0.05$.

Competition relief due to thinning significantly triggers growth of the remaining trees

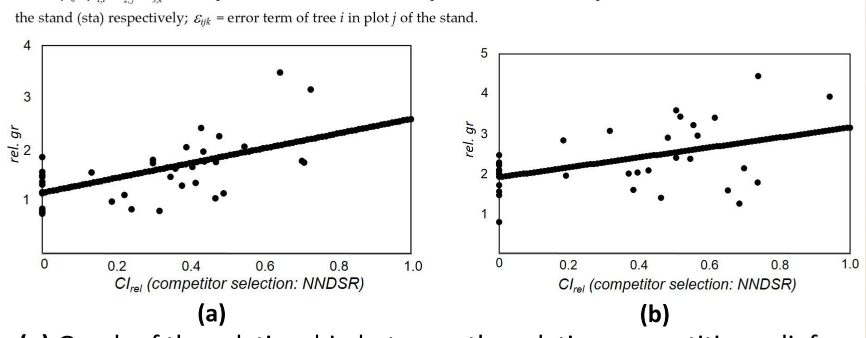
We elaborated linear mixed models (Gradel et al. 2017_3) for describing absolute growth (after thinning: 2009-2012) and relative growth (relative change in basal area growth after thinning (2009-2012) in comparison to the period before thinning (2007-2009):

$$abs.gr_{ijk} = (\beta_0)Intercept + (\beta_{1,i})DBH + (\beta_{2,i})CI_{diff} + (b_{2,j})plot + (b_{3,k})sta + \varepsilon_{ijk}$$

where β_0, $\beta_{1,i}$, $\beta_{2,i}$, $b_{2,j}$, $b_{3,k}$ are the parameter estimates of the intercept, the DBH, the CI_{diff} of the tree, the plot and the stand (sta) respectively; ε_{ijk} = error term of tree *i* in plot *j* of stand *k*

$$rel.gr_{ijk} = (\beta_0)Intercept + (\beta_{1,i})CI_{rel} + (b_{2,j})plot + (b_{3,k})sta + \varepsilon_{ijk}$$

where β_0, $\beta_{1,i}$, $b_{2,j}$, $b_{3,k}$ are the parameter estimates of the intercept, the CI_{rel} of the tree, the plot and the stand (sta) respectively; ε_{ijk} = error term of tree *i* in plot *j* of the stand.



(a) Graph of the relationship between the relative competition relief (CI_{rel}) and relative change in basal area growth (rel.gr) of larch. **(b)** Graph of the relationship between the relative competition relief (CI_{rel}) and relative change in basal area growth (rel.gr) of birch.

Model	Species	Variable	Fixed Effects	Com-petitor se-lection	Degrees of Free-dom	Model Parameter (Fixed Effects): Intercept	p-Value	CI_{rel}	p-Value	CI_{diff}	p-Value	DBH	p-Value	AIC of the Model
1	Birch	abs.gr	CI_{diff} + DBH	cone	31	−0.0009	0.0485			0.0003	0.0487	0.0002	0.0000	−400.95
	Birch	abs.gr	CI_{diff} + DBH	NNDSR	37	−0.0008	0.1638			0.0003	0.0214	0.0002	0.0000	−455.48
	Larch	abs.gr	CI_{diff} + DBH	cone	27	−0.0013	0.5163			0.0008	0.0440	0.0002	0.0000	−336.97
	Larch	abs.gr	CI_{diff} + DBH	NNDSR	31	−0.0018	0.2836			0.0006	0.0044	0.0002	0.0000	−388.26
2	Birch	rel.gr	CI_{rel}	cone	29	2.1084	0.0000	0.7111	0.0387					96.48
	Birch	rel.gr	CI_{rel}	NNDSR	29	1.9163	0.0000	1.2444	0.0052					87.82
	Larch	rel.gr	CI_{rel}	cone	31	1.4020	0.0000	0.6776	0.0159					70.17
	Larch	rel.gr	CI_{rel}	NNDSR	36	1.1756	0.0000	1.4156	0.0001					68.64

← Overview of the selected competition-growth models (fixed and mixed effect models). The different competitor selections are NNDSR = search radius class, based on the double NND; cone = cone method (Pretzsch 1995, Crocom 2007). CI_{diff} = difference in absolute competition before and after thinning; CI_{rel} = relative competition relief; DBH = diameter at breast height of tree i at the end of the vegetation period 2009; AIC= Akaike's Information Criterion.

DISCUSSION AND CONCLUSION
(Gradel et al. 2017_3)

- → diameter distribution and diameter CV were not greatly changed by thinning and on all plots BA growth, and on most plots the ingrowth of young trees was promoted by thinning;
- → an increase in stem number and basal area in the short period after the harvest events was noticeable;
- → the ratio between removed stem number and removed basal area (NG-ratio) indicated that, on most plots, smaller trees were preferentially removed (thinning from below);
- → clumping seems to be a characteristic feature of the disturbance prone birch and larch forests in Mongolia (Gradel et al. 2015);
- → our observation that the spatial tree distribution pattern tended towards regularity after thinning is common for many selective harvest regimes (e.g. thinned larch plots in Northern China (Lei et al. 2012));
- → thinning mostly promoted "de-clumping" and a tendency towards regular or random distribution.
- → Pukkula et al. (2015) concluded that for forest stands with irregular (clumped) tree distribution, the most profitable option is to remove the smaller trees in densely stocked areas and leave larger trees in sparsely stocked places (similar to the thinning approach in Altansumber);
- → the ability of the remaining trees to positively respond to competition relief was significant despite the fact that some trees had already reached a considerable age;
- → continuous cover forestry systems (Gadow et al. 2012; Vitikova et al. 2016) are considered a preferred option since exposition and sunblocking forest cover result in the disjunctive occurrence of permafrost (Savin et al. 1988, Kopp et al. 2014);
- → our results indicate that a more methodical and scientifically based forest management, comprising, among other strategies, repeated thinnings, could be established;
- → effects on stand stability and soil need to be further studied.

Forests close to the settlements are likely to experience more utilization pressure in the future. It is necessary to identify and enact sustainable management approaches (regional silvicultural treatments) and appropriate control measures to ensure ecologically sound management and to provide direction for forest utilization. Our results indicate that birch and larch trees respond to thinning with significant increases in absolute and relative growth. This finding could be a starting point for developing comprehensive forest management guidelines for both the larch and birch dominated stands. Reference plots and thinning trials, as shown in the example of the plots in Altansumber, can serve as a basis for analysis of silvicultural measures, training of prospective forest managers and creation of specific thinning models as well as providing a cooperation instrument for stakeholders with widely varying needs.

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