14 Appendix 1: Implementing topographical parameters: elevation, aspect, slope angle, and topographical wetness index

Topography modulates regional climate and controls the spatial patterns of the treeline limits (Holtmeier & Broll, 2009). We used the TanDEM-X 90 m digital elevation model (DEM) product (Krieger et al, 2013) for extracting the relevant spatial topographical parameters, namely: elevation, slope angle, and topographical wetness index (TWI). Prior to spatial topographical parameters extraction, the DEM was resampled from the 90-m cell spacing to a 30-m resolution with bilinear interpolation. We also investigated aspect, but when evaluating the topographical parameters for implementation, it did not have a strong effect. Slope angle and aspect were calculated in SAGA 2.3.2 (as QGIS 3.16.0 plugin) using Zevenberger & Thorne's second-order polynomial adjustment algorithm (1987). The TWI represents the moisture content, spatially distributed across the landscape. The TWI was calculated using the basic terrain analysis tool (SAGA GIS plugin) with the default setting of "the channel density" set to five. The final topography layers – elevation, slope angle, and TWI – were masked for areas of present surface water, such as Lower and Upper Lake Ilirney, small ponds, and rivers. We created the water mask by applying the land-water threshold technique to the Landsat-8 short-wave infrared (SWIR) 1 band (water reflectance <600) on a summer acquisition on 07.12.2018 with the Landsat spatial resolution of 30 m.

The topographical data (elevation, slope angle, TWI) were introduced in the source code of LAVESI as 30 x 30 m gridded input data, featuring a user-defined area. Based on this, the values are linearly interpolated to the internally used environmental grid of 20 x 20 cm tiles.

The seed dispersal that already depended on wind direction and speed, release height, and species-specific fall rates (Kruse et al, 2018, 2019) was further improved for this study by shortening the upslope dispersal distance and restricting it to locations below release height.

15 Appendix 2: Parameterisation of the influence of topography and wetness on tree presence and growth

To extract the dependence of tree presence from the topographic parameters – aspect, slope angle, and TWI – we used a high-resolution satellite acquisition from early summer in 2010 (ESRI World Imagery), which allows identification of single trees and covering a representative part of the study region. In the first step, 6488 sampling points for evaluation of the presence of trees were selected by stratified random sampling from 589 different possible combinations of elevation, slope angle, aspect, and TWI (Fig. A2.1A; Table A2.1). The samples cover 2% of the area (Fig. A2.1B), from southern forested areas via hummock tundra to the non-vegetated northern mountainous areas.

Table A2.1. Stratified random sampling categories. To conduct stratified random sampling, we used all possible combinations of elevation, slope, and aspect with breakpoints, forming the following categories:

Elevation:

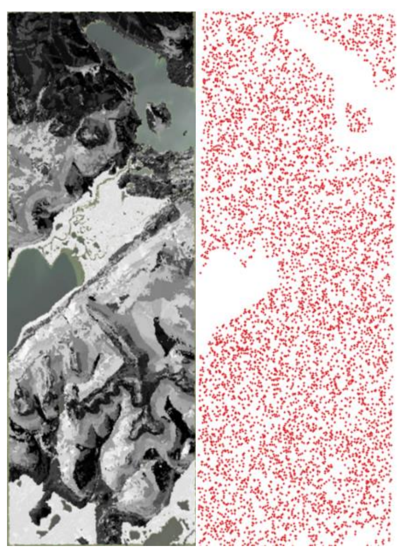
- 0-400 m
- 400-450m
- 450-500m
- 500-600m
- 600-650m
- 650-700m
- 700-1000m
- 1000-1500m

Slope:

- 0-2°
- 2-4°
- 4-6°
- 6-8°
- 8-10°
- 10-12°
- 12-16°
- 16-18°
- 18-20°
- 20-25°
- 25-50°

Aspect:

- 0-45°
- 45-90°
- 90-135°
- 135-180°
- 180-225°
- 225-270°
- 270-315°
- 315-360°



(A) (B)

Figure A2.1. (A) Visualisation of the combinations of elevation, slope angle, and topographic wetness index (TWI) in the area for parameterisation of the new topographic components in LAVESI with 589 categories distinguished, shown in grey shades, and (B) 6488 samples, marked as red dots.

A visual assessment of the established relationship shows that aspect does not play an important role in the presence of trees in the study region (Fig. A2.2). Areas both with and without trees show the same pattern of sample distributions in relation to the aspect data. In contrast, one can clearly see that trees prefer higher slope angles, rather than lower.

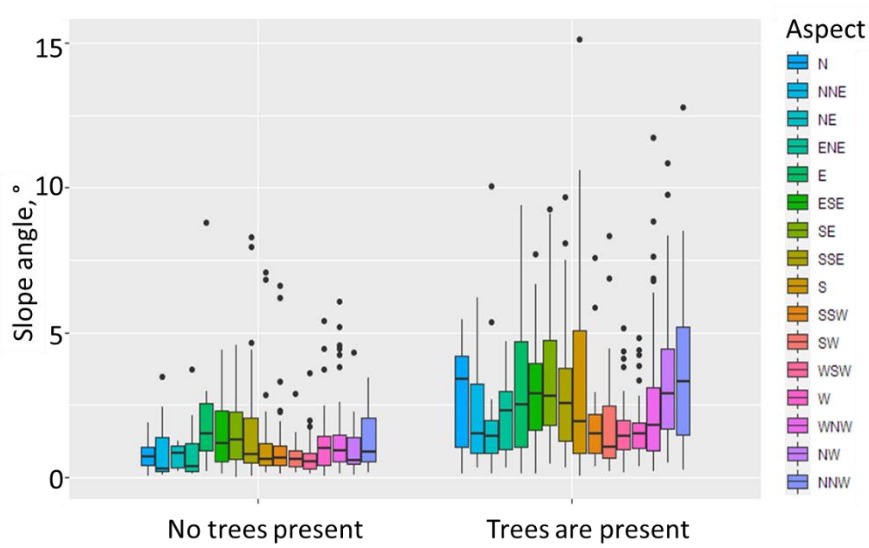


Figure A2.2. Tree presence depends strongly on slope angle and very slightly on aspect in the study region (based on 6488 stratified random samples). The patterns of aspect and slope angle combinations are generally similar for each direction of the treeless and tree areas, whereas areas with trees are found on slopes with higher angles in comparison to treeless areas for most of the aspect directions.

In consequence, we could separately establish two statistically significant linear models predicting tree presence (in percent of observations) depending on slope angle and TWI:

$$TrPrSA = e^{-0.5\,\frac{(slope\ angle - a)^2}{b^2}} = e^{-0.5\,\frac{(slope\ angle - 12.58)^2}{12.78^2}}, \qquad (3)$$

where TrPrSA is tree presence depending on slope angle, and a and b are coefficients (Table B1).

$$TrPrT = -c * TWI + 0.98 = -0.05 * TWI + 0.98, \tag{4}$$

where TrPrT is tree presence depending on TWI, and c is a coefficient (Table A2.2).

The models have good accuracy with residual standard errors of 0.013 (model under formula 3) and 0.011 (model under formula 4) and all significant coefficients (Tables A2.1 and A2.2).

The coefficients of these models were introduced into the model LAVESI to control environmental impact on individual growth simply by using the predicted forest presence at a certain location as a factor for the actual individual tree growth:

$$Envirgrowth = 0.5\, TrPrT + 0.5e^{2TrPrSA} \tag{5}$$

Table A2.1. Permutation test results for tree presence versus slope angle with three coefficients and their significance levels.

	Estimate	Standard error	t value	$Pr(>\lvert t\rvert)$
A	12.580	1.076	11.685	<0.0001
B	12.781	1.377	9.281	<0.0001

Table A2.2. Permutation test results for tree presence versus topographical wetness index (TWI) with an intercept, one coefficient, and their significance levels.

	Estimate	Standard error	t value	$Pr(>\lvert t\rvert)$
Intercept	0.980	0.045	21.879	<0.0001
c	-0.050	0.005	-9.955	<0.0001

16 Appendix 3: Calculation of above-ground biomass (AGB)

To predict the above-ground biomass (AGB) of each of the simulated larch trees, we used two separate models for needle and woody biomass established previously for the field sites in the study region (Shevtsova et al, 2021) based on a set of sampled trees (Shevtsova et al, 2020b) and simplified to estimate the biomass of all trees on the sites based on the recorded height of the present trees

(Kruse et al, 2020). Needle biomass of a living tree was calculated from the LAVESI-simulated tree height as follows:

$$AGBn = \frac{703.62}{1 + e^{-\frac{H - 579.5}{208.69}}} \text{ (g)}, \tag{1}$$

where AGB is above-ground biomass and H is tree height in cm. Wood biomass from a LAVESI-simulated living tree was calculated as follows:

$$AGBwl = \frac{78713.63}{1 + e^{-\frac{H - 793.64}{73.91}}} \text{ (g)}. \tag{2}$$