Introduction

Alpine Treeline Ecotones (ATEs) are transitional zones between subalpine Forest and Alpine (tundra) ecotones (@holtmeierSensitivityResponseNorthern2005, @winingsMappingAlpineTreeline2013) also referred to as upper-treeline (@elliottTreelineEcotones2017) and occur globally (@singhRemoteSensingAlpine2015, @baderGlobalFrameworkLinking2021). They span between the actual Timberline/Economic Forest Line though the Upper/Physiognomic-Biologic Forest Line and the tree species line which is adjoining the actual Alpine zone (@chhetriRemoteSensingGeographic2019, 1543). The position of the treeline is influenced by multiple factors at local and regional level, but temperature has been identified as the global driving factor (@kornerReassessmentHighElevation1998, @kornerWorldwideStudyHigh2004, @holtmeierSensitivityResponseNorthern2005, @baderVegetationStructureTemperature2007, @barredocanoImpactsClimateChange2020). The global pattern can be described by spatial patterns in the x-y plane (discrete or diffuse, Figure 1) and by changes in tree stature (abrupt or gradual, Figure 2) in a multi-dimensional space (@harschTreelineFormPotential2011, @baderGlobalFrameworkLinking2021).

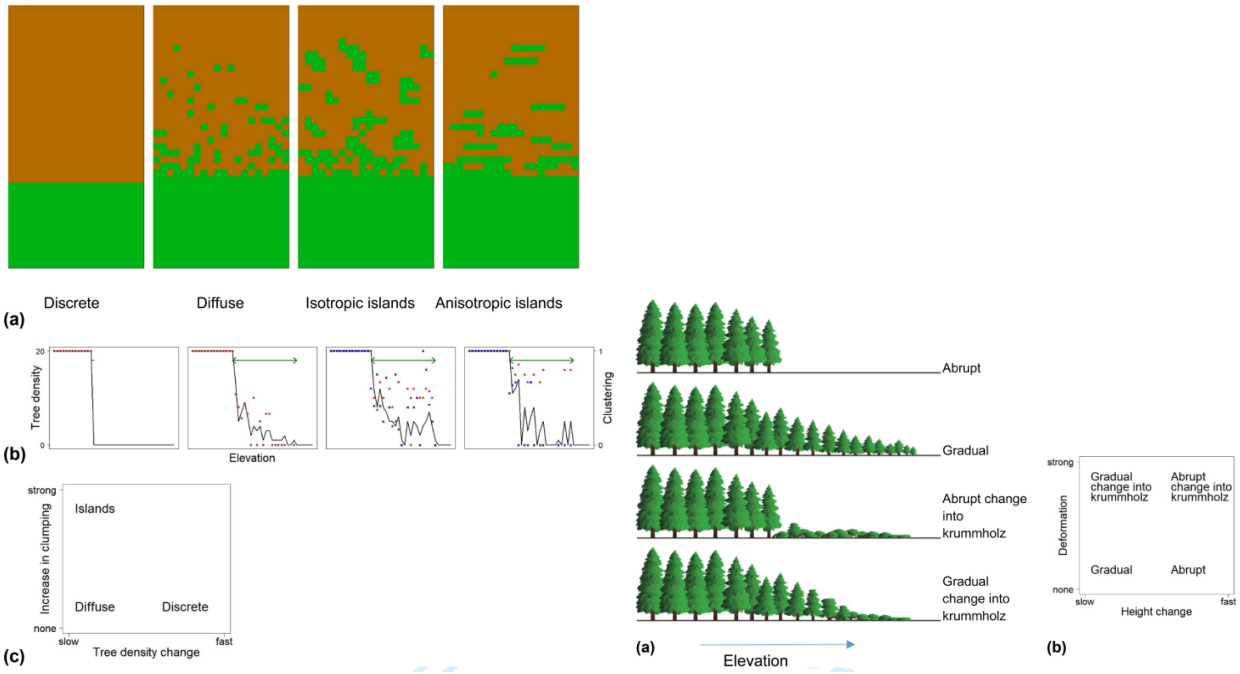

Figure 1: Left: Scheme of the spatial pattern of alpine treelines on the 2D x-y plane. a) Depicts the treeline as seen from above, while b) depicts the change of the treeline in the y direction (clustering of islands). c) Represents an abstraction of the pattern of treelines based on tree density change and the clustering of individual trees. Source: @baderGlobalFrameworkLinking2021, Figure 1. Right: Scheme of (discrete) tree stature/height change responding to change in elevation. a) Vertical cross section. b) Abstraction of tree stature change based on height change and deformation of tree shape. Source: @baderGlobalFrameworkLinking2021, Figure 2.

Although recognized, the distribution of ATE patterns have neither been mapped, nor been described yet, let alone explained. Earlier studies have identified abrupt, diffuse, island and krummholz spatial patterns of ATEs (@harschAreTreelinesAdvancing2009, @harschTreelineFormPotential2011, Figure 2). As seen, treelines dispaly a high variability and differ in multiple dimensions. A comparison of multiple studies suggest, that the different spatial patterns of ATEs reflect fundamental ecological controlling processes and that different ATEs react differently to climate change (@harschTreelineFormPotential2011, Figure 1) Figure 3.

To better understand and categorize ATEs a standardized description and terminology of spatial patterns has been proposed on hillslope and landscape scale by @baderGlobalFrameworkLinking2021, including hypotheses for the general mechanisms behind the patterns. The terminology and the multidimensional state-space

	a) Rate of change	b) Type of change	Controlling processes (first-level)	Controlling processes (second- and third-level)
2-D pattern	**Discrete**		Mortality above but not in the ecotone	Any type of damage or stress. If gradual, growth limitation above the ecotone
	Ecotone	**Diffuse**	Mortality within the ecotone	Environmental heterogeneity or stochasticity. And/or ongoing seed-limited colonization
		Island	Mortality within the ecotone	Positive feedback due to radiation damage, freezing damage, wind damage, snow redistribution (snow moulds, growing-season length), clustered seed dispersal, clonal reproduction
Tree stature	**Abrupt**	Into alpine	Mortality	Overheating, desiccation, photoinhibition, freezing damage, soil limitations
		Into krummholz	Dieback	Winter desiccation, snow moulds, browsing, abrasion
	Gradual	No krummholz	Growth	Tissue formation (limited by a lack of heat)
		Into krummholz	Growth and dieback	Tissue formation + winter desiccation, snow moulds, browsing, abrasion

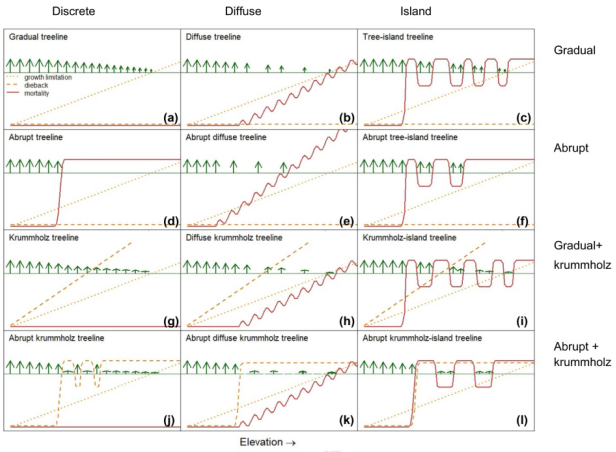

Figure 2: Left: Matrix of 2D spatial pattern, stature change and ecological processes which can contribute to the different types of ATEs. Source: @baderGlobalFrameworkLinking2021, Table 1. Right: Matrix of the multidimensional state space of treeline forms depicting extreme cases of the different dimensions. Columns represent the spatial patterns in the x-y plane and rows the change in tree stature (size and shape). The lines represents the hypothesized first-level ecological processes behind the patterns along an elevational gradient. The dotted line displays the growth limitation, the dashed line the dieback and the continuous line the mortality. Growth limitation always occurs while dieback only affects if krummholz is involved. Source: @baderGlobalFrameworkLinking2021, Figure 3.

can be most clearly understood from Figure 4.

After the definition and the characterization of the spatial patterns of ATEs, the following overview of ATE research shall serve as a basis for the workflow proposed in this methodological paper to globally detect ATEs.