142. Jahrgang (2025), Heft 2, S. 113–136

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

Altitudinal distribution of Stone Pine (*Pinus cembra* L.) in the Styrian Alps as indication for silvicultural stability and resilience strategies

Höhenverbreitung der Zirbe (*Pinus cembra* L.) in den steirischen Alpen als Hinweis für waldbauliche Stabilitäts- und Resilienz-Strategien

Roland Koeck[1*], Michael Kessler[1], Yasmin Dorfstetter[1], Iris Oberklammer[2], Ralf Klosterhuber[3], Franz Starlinger[4], Heinz Lick[5], Michael Englisch[4], Judith Schaufler[4], David Keßler[4], Manfred J. Lexer[1], Harald Vacik[1]

Keywords: Sample-based inventory, forest vegetation zone, productivity, site factors

Schlüsselbegriffe: Stichprobeninventur, Waldvegetationszone, Produktivität, Standortsfaktoren

Abstract

Stone Pine (*Pinus cembra* L.) grows preferentially in the higher elevations of the European Alps and Carpathians with a slow juvenile growth but exhibits a strong economic potential. This study provides an insight to the altitudinal distribution of Stone Pine in the Styrian Alps as indication for forest management concepts to increase the stability and resilience of alpine mountain forests in the context of a changing climate. In the FORSITE project (Dynamic Forest Site Classification), data concerning relief, soil, ground vegetation, tree- and stand characteristics were gathered at 1803 forest

[1] Institute of Silviculture, University of Natural Resources and Life Sciences, Peter Jordan Str. 82, 1190 – Vienna, Austria
[2] Institute of Forest Ecology, University of Natural Resources and Life Sciences, Peter Jordan Str. 82, 1190 – Vienna, Austria
[3] WLM – Wald-Landschaft-Mensch, Innstraße 23/3/11, 6020 - Innsbruck, Austria
[4] BFW – Austrian Research Centre for Forests, Department of Forest Ecology and Soil, Seckendorff-Gudent-Weg 8, 1131 – Vienna, Austria
[5] Styrian Government, Styrian Forest Commission, Ragnitzstraße 193, 8047 - Graz, Austria
* Corresponding author: Roland Koeck, roland.koeck@boku.ac.at

site investigation plots and analyzed as basis for creating a forest site classification system for the Austrian province of Styria. Out of the total plots Stone Pine was found on 98 forest sites ranging between 1250 m and 2050 m asl. Stone Pine is typically dominant in the forest stands within the upper forest vegetation zones (very cold, cold and moderately cold) with shares >50 %. The subdominant admixture of Stone Pine in the cool forest vegetation zones (very cool, cool and moderately cool) is emphasized. A tendency for increasing productivity (Site Index 100) related to decreasing elevation was found. The potential drivers for the current distribution of Stone Pine in Styria, the economic use, silvicultural measures to enhance the resilience of mountain forests and potential risks are discussed.

Zusammenfassung

Die Zirbe (*Pinus cembra* L.) wächst bevorzugt in den höheren Lagen der europäischen Alpen und Karpaten und weist dabei ein langsames Wachstum in der Jugend, aber ein hohes wirtschaftliches Potenzial auf. Diese Arbeit gibt einen Einblick in die Höhenverbreitung der Zirbe in den steirischen Alpen als Hinweis für mögliche Waldbewirtschaftungskonzepte zur Erhöhung der Stabilität und Widerstandsfähigkeit von alpinen Bergwäldern im Klimawandel. Im Zuge des FORSITE Projektes (Dynamische Waldtypisierung) wurden Daten zu Relief, Boden, Bodenvegetation, Baum- und Waldbestand an 1803 Stichprobenflächen erhoben und als Grundlage für die Erstellung einer Standortsklassifikation für das Bundesland Steiermark verwendet. Von dieser Gesamtzahl wurde die Zirbe auf 98 Erhebungsflächen zwischen 1250 m und 2050 m ü.M. gefunden. Die Zirbe ist dabei in den Waldbeständen der oberen Waldvegetationszonen (sehr kalt, kalt und mäßig kalt) mit Anteilen >50 % dominant. Hervorgehoben wird die subdominante Beimischung von Zirbe in den Erhebungsbeständen der kühlen Waldvegetationszonen (sehr kühl, kühl und mäßig kühl). Es wurde eine Tendenz zu steigender Produktivität (Site Index 100) bei abnehmender Seehöhe festgestellt. Die potenziellen Treiber für die aktuelle Verbreitung der Zirbe in der Steiermark, die wirtschaftliche Nutzung, waldbauliche Maßnahmen zur Erhöhung der Widerstandsfähigkeit der Bergwälder und mögliche Risiken werden diskutiert.

1 Introduction

Stone Pine (*Pinus cembra* L.), also known as Swiss Stone Pine, Austrian Stone Pine, Arolla Pine or Cembran Pine, is a tree species which grows preferentially in the higher elevations of the European Alps (Körner 1998, Willner & Grabherr 2007, Badino et al. 2018) and Carpathian mountain ranges (Caudullo *et al.* 2017, Popa *et al.* 2017, Nagavciuc *et al.* 2020, Zieba *et al.* 2020). Due to its considerable frost resistance, it can withstand harsh climatic conditions on sites, where temperature is one of the limiting factors for tree growth (Hätenschwiler & Körner 1995, Körner 2003). This is a capability, which signifies Stone Pine (SP) as a tree species of the upper conifer forest belt of these European mountain ranges, where in some regions SP shapes the timber and tree lines (Körner 1998). However, SP does not occur consistently within this upper forest belt of the respective mountain ranges. In some alpine regions it grows dominantly by forming vast SP stands, while in neighboring regions it may be missing or growing only sparsely at the tree and timber lines. However, the reasons for the inconsistent occurrence of SP are not well understood yet. A spatially coarse European distribution map shows that the Styrian SP stands are situated at the easternmost border of the alpine SP chorology (Fig. 1, Caudullo *et al.* 2017).

SP is a tree species with slow juvenile growth (Mayer 1992, Ulber *et al.* 2004, Schütt *et al.* 2008), a fact which in forest management sometimes requires silvicultural regulation of growing space for SP in relation to coexisting and faster growing tree species such as Norway Spruce (*Picea abies* (L.) Karst.) or European Larch (*Larix decidua* Mill.) (Gugerli *et al.* 2022). SP exhibits a strong economic potential, for its timber used for furniture, its non-wood forest products such as essential oil from the needles and other tree compartments (Apetrei *et al.* 2013, Chizzola *et al.* 2021, Kadim *et al.* 2023, Czakert *et al.* 2024), liqueur from the cones and further health related products such as wood chips favored for their smell (Grote *et al.* 2021). This makes SP an interesting species in the context of the economic aspects of forest management. Under the harsh climatic conditions that prevail at the timber line of the Alps and Carpathians, SP additionally plays an important role in protection forests. In fact, on steep slopes of the mountain ranges SP exerts an important protective function against natural hazards such as avalanches, rockfall, flooding, soil erosion, landslides and debris flow (Jandl *et al.* 2018).

Between 2018 and 2023 the project 'Dynamic Forest Site Classification' (FORSITE) was carried out in the Austrian province of Styria (Fig. 1). Based on a stratified sampling design data including information on relief, soil, vegetation, tree and stand characteristics were collected. Combined with other regionalized information such as climate parameters (Lehner *et al.* 2023 & 2024a & 2024b) and information on geological substrate (Simon *et al.* 2021, Wilhelmy 2021, Brandstätter *et al.* 2023), these data were used for developing a forest site classification model and for creating detailed forest site maps covering the entire forest area of Styria (Landesforstdirektion Steiermark 2023).

A key question arose, whether the actual occurrence of SP is restricted to the upper forest belts of the Styrian Alps or whether it also extends into lower altitudes. The present paper aims to explore:

(i) The current distribution and dominance of SP in forest stands along an altitudinal gradient
(ii) The variation of productivity of SP along an altitudinal gradient
(iii) The role of site factors in explaining the current distribution of SP

Based on the gathered insights we finally provide recommendations on the cultivation of SP to increase tree species diversity and the resistance and resilience of forest ecosystems in Styria.

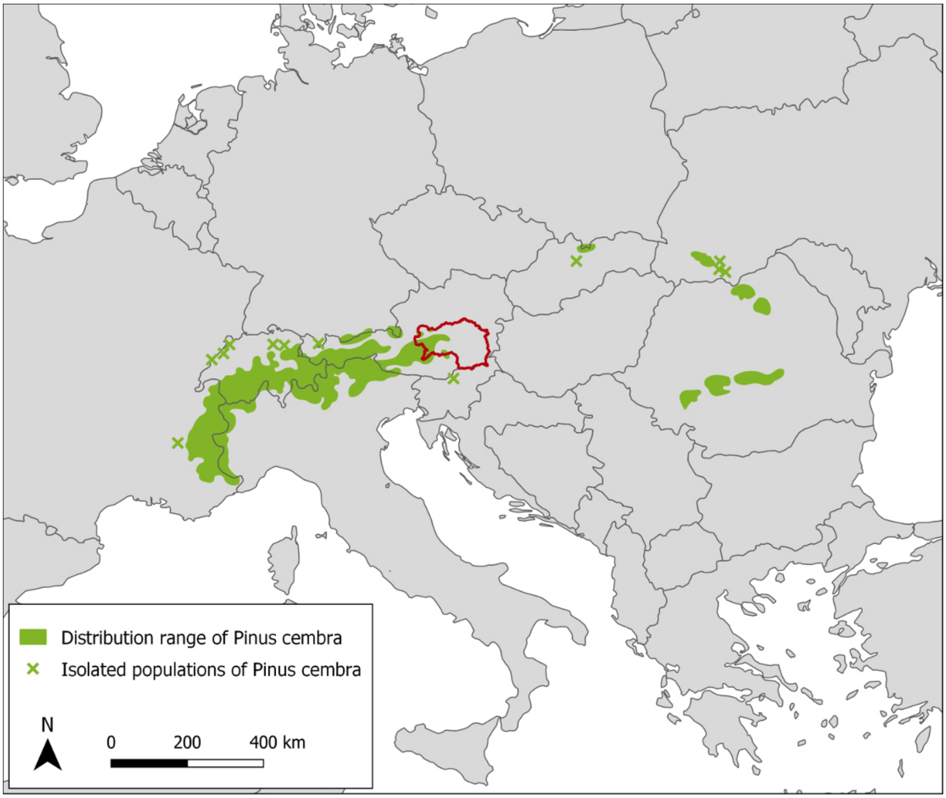

Figure 1: Location of the project area, the Austrian province of Styria (red outline) in Europe, and the coarse-scale map of European SP (Pinus cembra) distribution (Caudullo et al. 2017).

Abbildung 1: Lage des Projektgebietes im österreichischen Bundesland Steiermark (rot umrandet) in Europa und die großmaßstäbliche Karte zur Verteilung von SP (*Pinus cembra*) in Europa (Caudullo *et al.* 2017).

2 Methods

2.1 Data investigation

In the FORSITE project, field data on relief, soil, ground vegetation, tree- and stand characteristics were gathered at 1803 forest site investigation (FSI) plots and analyzed as basis for creating a forest site classification system for the Austrian province of Styria. The distribution of the FSI plots was oriented towards covering the entire forest area of Styria and at representing the diversity of geological substrates, relief types, slope expositions and climatic forest vegetation zones (see below for an explanation of the concept of forest vegetation zones). The FSI data was analyzed (a) regarding the occurrence of SP in a 50 x 50 m forest stand plot, categorized into dominance classes and (b) regarding tree-level measurements such as diameter at breast height (DBH), tree height and increment cores from a tree sample. Additionally, soil parameters, ground vegetation and general relief information including elevation above sea level were analyzed for all FSI plots where SP was present. Based on measured top height and available information on tree age from increment cores, a site index as the dominant height of a tree species at the age of 100 years (SI100) was calculated to characterize the growth potential of SP at specific forest sites.

During the field campaign for creating the FSI database, Vertex was applied for measuring tree height and an increment borer for extracting increment cores. Tree ring analysis was carried out in the dendrological laboratory using microscope technique and synchronization of tree ring series. Ground vegetation was assessed by using an extended Braun-Blanquet (Braun-Blanquet 1964) scale and analyzed to assign its corresponding forest community (phytosociology according to Willner & Grabherr 2007). Soil parameters were assessed in hand-digged soil pits using the Austrian Soil Classification System (Nestroy *et al.* 2011) and the field assessment methods of the Austrian Forest Soil Monitoring (Blum *et al.* 1989) as well as the German instructions for soil mapping (KA5; Ad-Hoc-AG Boden 2005) for the assessment of soil physical parameters. At a subset of 400 selected FSI plots, field assessments were complemented with physical and chemical laboratory analysis of collected soil samples. For the remaining FSI plots without laboratory analysis, the respective parameters were based on the analyzed data. The base saturation class of the forest sites, which is an indicator for nutrient supply (Englisch *et al.* 2023, Kölling 1996), was derived by combining geological substrate information (Brandstätter *et al.* 2023, Simon *et al.* 2021, Wilhelmy 2021) with chemical parameters of the soil layers and with indicator values of ground vegetation species (Ellenberg *et al.* 1992).

2.2 The concept of forest vegetation zones

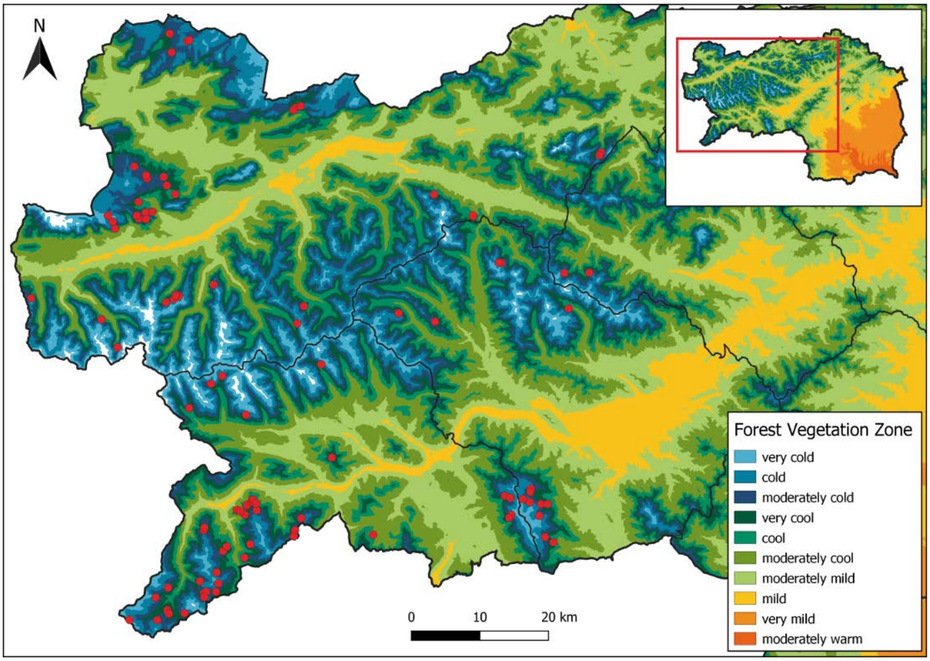

Figure 2: Distribution of forest site investigation plots (FSI) with presence of Stone Pine (SP) over the current Forest Vegetation Zones (FVZ) in the Austrian province of Styria.

Abbildung 2: Verteilung der Waldstandorts-Erkundungsflächen (FSI) mit Zirben-Präsenz (SP) über die aktuellen Waldvegetationszonen (FVZ) im österreichischen Bundesland Steiermark.

For analyzing the altitudinal distribution of SP, the concept of forest vegetation zones (FVZ) was applied, being the indicator for the warmth-gradient of the forest site model. FVZ were defined for the purpose of a climatic stratification of the Styrian forest area. The concept of the FVZ as used in FORSITE is dynamic, as those may move in the landscape with changing climate and was developed as a climate sensitive alternative to the historic and static altitudinal zones for Austrian forests (Kilian *et al.* 1994) ranging from high subalpine levels to colline lowlands. Ongoing climate change was the main motivation for this dynamic concept. Hence, the altitudinal range of the FVZ varies according to the specific regional climates and relief types (Englisch *et al.* 2023). Under current climatic conditions, Styria is classified into ten FVZ spreading from the uppermost and mountainous 'very cold' to the 'moderately warm' FVZ in the Styrian flatlands (Fig. 2). Table 1 provides additional information on the six upper FVZ with current presence of SP in Styria. According to the FVZ concept used in FORSITE, SP is a characteristic tree species of the uppermost 'very cold' and 'cold' conifer FVZ.

Table 1: Forest Vegetation Zones (FVZ) with current presence of Stone Pine (SP) in Styria including their corresponding characteristic tree species and the historic terms of the altitudinal zones.

Tabelle 1: Waldvegetationszonen (FVZ) mit aktueller Präsenz von Zirbe (SP) in der Steiermark, charakteristische Baumarten und die korrespondierenden Bezeichnungen der historischen Höhenstufen sind inkludiert.

Acronym of FVZ	**Forest Vegetation Zone (FVZ)**	**Type of Forest Zone**	**Characteristic tree species**	**Historic term - altitudinal zone**
vcd	very cold	conifer	SP	high subalpine
cd	cold	conifer	SP, NoS	middle subalpine
mcd	moderately cold	conifer	NoS	lower subalpine
vco	very cool	conifer	NoS, SF	upper montane
co	cool	mixed and conifer	EB, SF, NoS	high montane
mco	moderately cool	mixed	NoS, SF, EB	middle montane

Tree species acronyms: SP…Austrian Stone Pine (*Pinus cembra*); NoS…Norway Spruce (*Picea abies*); SF…Silver Fir (*Abies alba*); EB…European Beech (*Fagus sylvatica*)

The Styrian site classification system combines three axes for defining distinct forest site types:

(I) the forest vegetation zones (FVZ) ranging from 'moderately warm' to 'very cold' as indicator for the warmth-gradient (Tab. 1, Fig. 2),
(II) the water regime class and
(III) the base saturation class as indicator for nutrient supply (Tab. 2).

The synopsis of the three axes defines each site type based on the specific forest site conditions.

Table 2: Distribution (%) of the 98 FSI plots with SP presence over the Base Saturation Classes.

Tabelle 2: Verteilung (%) der 98 FSI Flächen mit Zirben-Präsenz (SP) über die Basensättigungsklassen.

c	**g**	**r**	**m**	**u**	**e**
23 %	2 %	5 %	5 %	45 %	20 %

Base Saturation Class with corresponding percentages of base saturation: "c"…carbonatic (> 90 %, base saturated, but lopsided base saturation), "g"…base saturated (> 90 %), "r"…base rich (60 – 90 %), "m"…moderate base saturation (35 – 60 %), "u"…low base saturation (8 – 35 %), "e"…extremely low base saturation (< 8 %).

The corresponding forest site maps cover the entire forest area of Styria, providing spatially explicit information at a resolution of 30 m x 30 m and are digitally available for local forest owners and managers (Landesforstdirektion Steiermark 2023).

2.3 Data analysis

Data analysis was restricted to the Styrian FSI plots showing presence of SP at the forest stand level (50 x 50 m). Information about the FVZ and the base saturation class at each FSI plot was extracted from the spatially modelled maps of the Styrian forest site classification system. The dominance classes of SP were derived from the 50 x 50 m stand data pool, whereas the growth potential of SP at the forest sites (SI_{100}) were calculated based on data from the tree sample of the FSI plot data base. The presence of *Rhododendron* species in ground vegetation was derived from the respective Braun-Blanquet phytosociological data of the FSI plots. Response-variables such as presence of SP, dominance class and SI_{100} were analyzed along gradients of (a) FVZ and (b) base saturation class by using descriptive statistics (gradient-analysis). Information on *Rhododendron* species in ground vegetation was obtained from a presence-analysis in the respective phytosociological data set.

3 Results

Out of the Styrian FSI data pool (1803 plots), SP was found on 98 forest sites. The current occurrences of SP in Styria range between 1250 m and 2050 m asl while the uppermost limit of the 'very cold' FVZ (the coldest one in Styria - 'vcd') is situated around 2300 m asl.

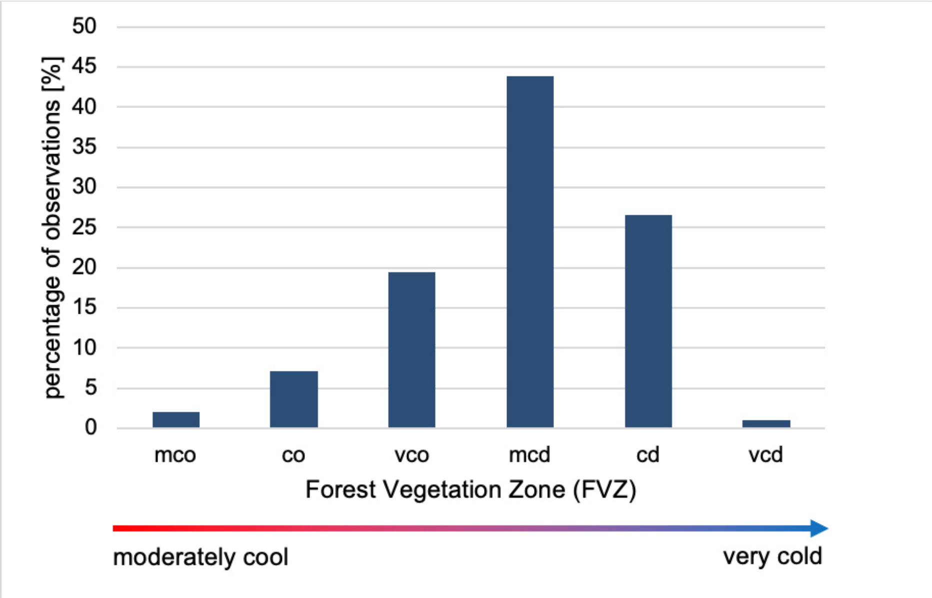

Figure 3: Distribution of the FSI plots (n = 98) with presence of Stone Pine (SP) over the Forest Vegetation Zones (FVZ).

Abbildung 3: Verteilung der Waldstandorts-Erkundungsflächen (FSI, n = 98) mit Zirben-Präsenz (SP) über die Waldvegetationszonen (FVZ).

The sampled data do not describe the whole distribution of SP in Styria but provide information about its altitudinal spread, its dominance and its growth potential (productivity) in dependence of forest site parameters. The spatial distribution of Styrian FSI plots with SP occurrence (Fig. 2) shows the main areas where this tree species forms forest stands, like Gurktaler Alpen, Zirbitzkogel, Niedere Tauern, Dachstein or Totes Gebirge. Even the easternmost sites of Austria with current SP forest stands which can be found in the Gesäuse mountain range (Carli 2014, Langmaier & Hochbichler 2015), were covered by the survey.

All 98 FSI plots showing presence of SP were assigned to the corresponding FVZ of the forest site maps. Data analysis shows that SP occurs within the upper six FVZ in the western mountain ranges of the province of Styria (Fig. 2 and Fig. 3). The main share of the FSI plots showing presence of SP is situated within the 'moderately cold' FVZ (44 %), while 26 % of the SP plots are located in the 'cold' and 19 % in the 'very cool' FVZ. In the 'cool' FVZ 7 % of the plots were found (Fig. 3). The uppermost 'very cold' and the lowermost 'moderately cool' FVZ with occurrence of SP only show a small number of FSI plots with SP presence.

The distribution of the 98 FSI plots over the base saturation classes (Tab. 2) shows that SP presence is concentrated on forest sites with the classes 'u' and 'e' (low base saturation) but also with the carbonatic class 'c' (high, though lopsided base saturation).

The dominance classes of SP (i.e. shares of this tree species in the forest stands) among the FSI plots were analyzed on the 50 x 50 m sample plot level. Figure 4 shows that within the upper three cold FVZ ('vcd', 'cd', 'mcd'), SP is typically dominant (shares of 51-100 %). It became evident that also in the lower three cool FVZ ('mco', 'co', 'vco'), SP can establish as subdominant tree species (shares of 26-50 %) (Fig. 4).

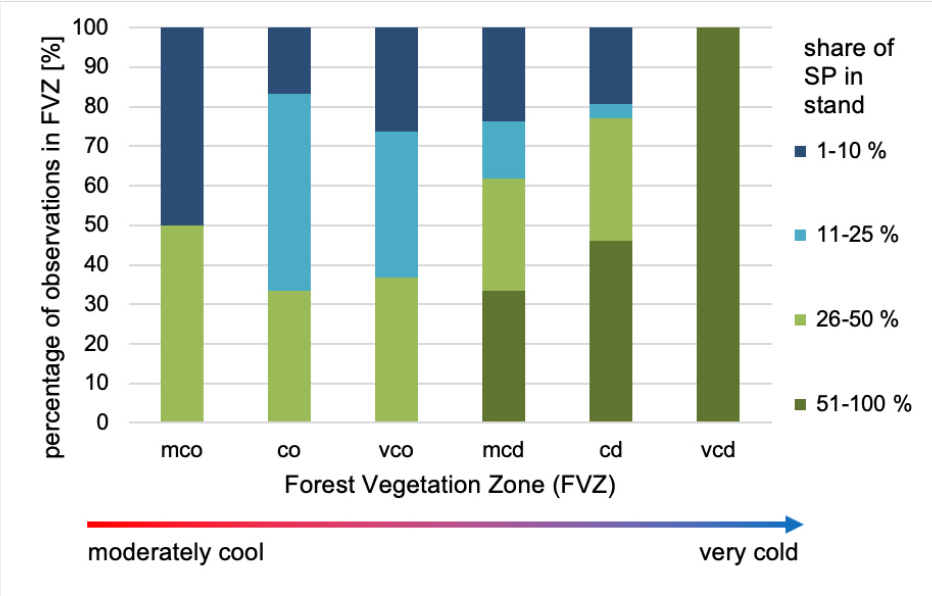

Figure 4: Proportional representation of dominance classes of Stone Pine (SP) in the Forest Vegetation Zones (FVZ) among analyzed forest site investigation plots (FSI, n = 98).

Abbildung 4: Proportionale Darstellung der Dominanzklassen von Zirbe (SP) in den Waldvegetationszonen (FVZ) innerhalb der analysierten Waldstandorts-Erkundungsflächen (FSI, n = 98).

As expected in terms of productivity, a tendency of increasing SI_{100} values with decreasing elevation was identified (Fig. 5). Only in the cool FVZ the situation is slightly different, which could be explained by partly low base saturation values at analyzed forest sites, which besides low temperatures can also cause low productivity.

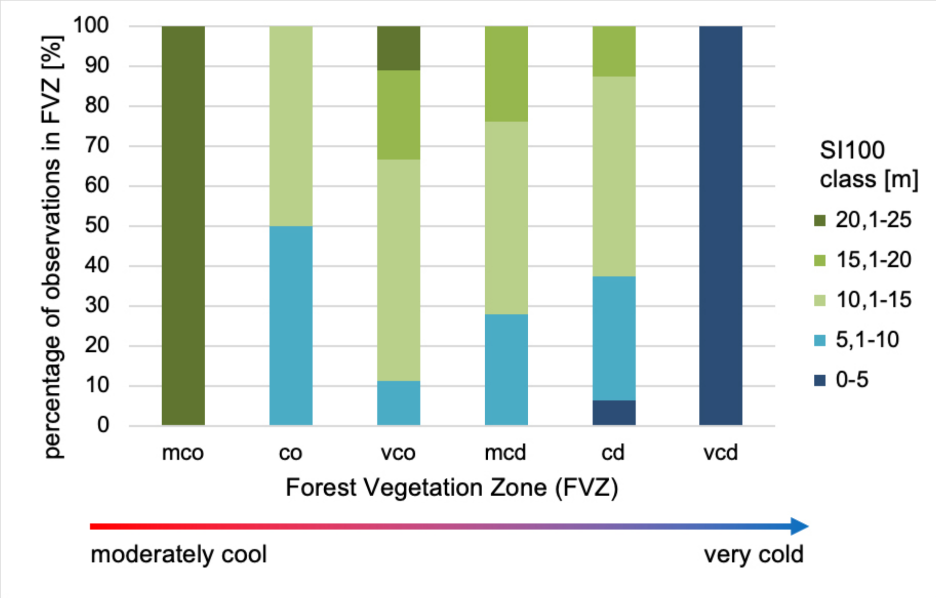

Figure 5: Proportional representation of the Site Index classes (SI_{100}) of Stone Pine (SP) over the Forest Vegetation Zones (FVZ) in the analyzed forest stands derived from the FSI plot (n = 98) data.

Abbildung 4: Proportionale Darstellung der Site-Index-Klassen (SI_{100}) von Zirbe (SP) über die Waldvegetationszonen (FVZ) in den analysierten Waldbeständen, hergeleitet von den Waldstandorts-Erkundungsflächen (FSI, n = 98).

Analysis of the ground vegetation reveals that 60 % of the FSI plots with presence of SP also show occurrence of *Rhododendron* species (*Rhododendron ferrugineum* and *Rhododendron hirsutum*), which also indicate grazing activities by domestic animals (alpine pastures).

4 Discussion

4.1 Potential drivers for SP occurrence in Styria

In the Alps the occurrence of forest stands with dominant or sub-dominant SP is commonly expected to be restricted to the upper-subalpine zone (which corresponds to the 'cold' and 'very cold' FVZ), with a related altitudinal range of approximately 1700 m to 2400 m asl in the Eastern Alps (Willner & Grabherr 2007; Mucina *et al.* 1993; Mayer 1974). Results of the current investigations indicate that in Styrian forests SP can occur widespread over an altitudinal range between 1250 m and 2050 m asl. The fact that in Styrian mountain ranges the presence of SP extends downwards to the moderately cool FVZ (‘mco’) and that forest stands with SP also occur in lower altitudes around 1500 m asl was unexpected. The proportion of FSI plots with SP occurrence in the ‘very cool’ FVZ (‘vco’, Fig. 3) should be particularly highlighted, as for this FVZ the thermally more sensitive and demanding Silver Fir (*Abies alba* Mill.) is mentioned as characteristic tree species (Tab. 1). The fact that in the Styrian Alps SP can also form forest stands at elevations around 1500 m asl is additionally supported by the spatial extension of the category of mixed Norway Spruce, European Larch and Austrian Stone Pine stands in the tree species map of the Austrian Forest Inventory (BFW 2025). In his later works also Mayer (1992) describes a rather wide altitudinal range of SP in the Austrian Alps. In addition, it has to be taken into account, that the current projections of the forest vegetation zones in the FORSITE project are based on the climate data of the last 30 years, which considers a shift of the altitudinal ranges to higher elevations to some extent due to the increasing temperatures. However, most of the investigated forest stands originate from the 19th century, where the climate might have placed the current forest vegetation zones some 200-300 m lower and not all forest stands have yet been able to adapt to this change.

The potential drivers for the presence of SP in forest stands, especially within the three lower situated cool FVZ (‘mco’, ‘co’, ‘vco’), could be of agricultural or forestal nature. Many SP stands are associated with alpine pasture activities, which create rather open forest stands where *Rhododendron* species (*Rhododendron ferrugineum* and *Rhododendron hirsutum*) can establish. These *Rhododendron* species host the fungal species *Chrysomyxa rhododendri*, which in turn can infect Norway Spruce (*Picea abies* L.) individuals as an intermediate host and hence diminish spruce competitivity (Oberhuber *et al.* 1999). Reduced vitality of Norway Spruce can thus lead to improved light conditions for SP for gaining or maintaining dominance on mountain forest sites situated at lower altitudes, where it co-exists with Norway Spruce or European Larch. In fact, at 60 % of the analyzed FSI plots presence of *Rhododendron* species was identified in the ground vegetation. Furthermore, the rather open structure of alpine forests influenced by pasture activities reduces competitive stress and can thus facilitate SP in relation to Norway Spruce.

Forest management might be another driver of SP dominance considering the findings in forest history of the western Styrian mountain district Murau by Johann (2021). The studies demonstrate that since the 14th century forests and water of the district were used for the industrial production of iron, copper, silver, etc. In order to maintain the supply of charcoal for the blast furnaces, vast forest areas were clear-cut, with only small forest strips remaining between the harvested areas. First mentioned in the year 1775, artificial regeneration activities using the sowing technique were applied to countervail the deforestation process. Extensive afforestation activities based on the planting of seedlings are documented for this area around the mid of the 19th century, involving mainly Norway Spruce, European Larch and Austrian Stone

Pine. During this time also most of the mining activities were stopped and the last blast furnace in the village of Turrach was abandoned in the year 1909, which facilitated the re-establishment of forest cover in this Styrian district (Johann 2021). Various forest stands with dominant SP in Styria are thus assumed to result from artificial regeneration, which is in agreement with Lick (1991), who describes the plantations of SP stands at 1300 m.a.s.l.

Furthermore, the cooler climate in Austria during the estimated establishment of current SP stands 150 years ago (Formayer *et al.* 2009, Liu 2024) could have contributed to a better growth performance of SP in relation to the thermally more sensitive and demanding Norway Spruce and European Larch at some forest sites and hence might have facilitated SP dominance. However, under currently increased thermal conditions SP is still vital and growing successfully within the forest stands at the analyzed FSI plots in Styria.

Another important natural driver for SP distribution is the Spotted Nutcracker (*Nucifraga caryocatactes*). This bird species predominantly creates its seed caches in the already forested area and supports seed dispersal of SP at both the upper and lower elevational range of the current distribution (Neuschulz *et al.* 2018). In the long run, this can also lead to a higher altitudinal range of SP depending on the food availability for the Spotted Nutcracker.

A differentiation of whether a forest stand with dominance of SP was established by afforestation activities or by natural forest succession was not carried out in this study. Answering this question may be a challenging task due to a lack of documentation.

4.2 Silvicultural aspects regarding Stone Pine

As the analysis of presence, dominance and growth potential of SP proved its suitability on specific forest sites of the upper six FVZ, SP cultivation seems to be a viable option for forestry within these forest areas, if effects of competition are particularly considered by silvicultural management. Table 3 shows an evaluation with regard to the potential for SP cultivation and silvicultural treatment demand on different forest sites depending on FVZ and base saturation classes.

Table 3: Distribution of the Base Saturation Classes within the Forest Vegetation Zones (FVZ) over the Styrian forest area, displaying the related silvicultural treatment demand (STD) for Stone Pine (SP) cultivation, values in hectare (ha).

Tabelle 3: Verteilung der Basensättigungsklassen innerhalb der Waldvegetationszonen (FVZ) über die steirische Waldfläche; der zugehörige waldbauliche Behandlungsbedarf (STD) für Zirben-Kultivierung (SP) ist dargestellt, Werte in Hektar (ha).

FVZ	Base Saturation Class					
	c	G	R	m	u	e
vcd	664	77	218	432	669	191
cd	11330	987	1518	3501	11807	2991
mcd	18294	2520	2669	4656	23713	9262
vco	19501	4915	3695	5573	32192	16219
co	29333	11076	8199	11161	51486	23911
mco	57112	27901	21138	27833	89904	28669

Sector A	... coldest FVZ, high shares of SP occurrence, low STD
Sector B	... potentially high silvicultural demand for SP, medium STD
Sector C	... lower two cool FVZ, cultivation of SP possible, medium to high STD
Sector D	... nutrient rich sites, very high STD, low current occurrence of SP

Within the two uppermost FVZ ('vcd' and 'cd') low silvicultural treatment demand for SP is assumed (sector A in Tab. 3), as SP either is already present and should be able to establish through natural regeneration or could be successfully planted and subsequently form forest stands as the dominant tree species. A detailed analysis of regeneration data at the FSI plots was hampered by the fact, that natural regeneration is hindered at several sites due to the browsing impacts of wild ungulates.

Especially in the lower situated four FVZ ranging from 'mcd' to 'mco', cultivation of SP could be an important silvicultural option on forest sites with extremely low base saturation values (base saturation class 'e'), as the set of suitable tree species is limited there ('e' in sector B of Tab. 3; this applies to 52,581 ha of the Styrian forest area). On such sites, SP could substantially increase forest ecosystem stability and resilience, as it would increase tree species diversity and could be planted as an alternative to the currently bark-beetle threatened Norway Spruce and thus could help mitigating negative effects of climate change on forest ecosystems. Given the fact that FVZ 'vco' and 'mcd' are pure conifer forest zones, related sites with suboptimal nutrient supply can be described as areas with a potentially high silvicultural demand for SP cultivation ('c', 'g' and 'u' in sector B of Tab. 3). On such sites, silvicultural treatment demand (*e.g.* growing space regulation) for SP cultivation would be medium as SP faces competition from Norway Spruce or European Larch.

In contrast, on nutrient rich forest sites with high productivity (base saturation classes 'r' and 'm') cultivation of SP would require intense silvicultural treatment like growing space regulation, as SP would face strong competition from *e.g.* Norway Spruce (sector D in Tab. 3; this is the case for 84,925 ha of the Styrian forest area). On such forest sites cultivation of SP would be mainly motivated by economic reasons and establishment of SP stands would only be possible in a forest-plantation. On sites of the lower FVZ 'co' and 'mco' showing suboptimal nutrient supply, SP could only be cultivated with medium to high silvicultural treatment demand (sector C in Tab. 3), as SP would face competition from several tree species like Norway Spruce or European Beech (*Fagus sylvatica* L.).

On several different forest site types in Styria, SP cultivation could substantially increase forest ecosystem stability and resilience. Under current climate, 213,582 ha of the Styrian forest area can be regarded as suitable for the cultivation or natural regeneration of SP (sectors A and B in Tab. 3), postulating a low to medium silvicultural treatment demand on these areas for achieving this aim. Existing forest stands with dominant and subdominant SP show a tendency towards successful natural regeneration of SP, hence the maintenance of SP dominance in such forest stands is assumed to require minor silvicultural treatment. However, for successful SP regeneration, whether natural or artificial, wild ungulate regulation is required. The fact that planted SP has been found to be susceptible to game damage (Gugerli *et al.* 2022) puts even a stronger emphasis on game regulation measures for any SP cultivation or afforestation activities in mountain forest ecosystems in order to avoid or mitigate these threats.

Also the potential risks for SP cultivation regarding pests and diseases must be considered. SP can face *e.g.* infection with *Dothistroma septosporum* (a fungal disease - Pine needle blight) which can lead to brown needles especially in the lower section of tree individuals (Kirisits & Cech 2007), although reports about related SP die-back were not found until now. But the bark-beetle species *Ips amitinus* occuring in the Austrian Alps above 1000 m asl and is spreading up to the tree-line, can potentially affect the conifer species in this altitudinal zone and hence also SP (Stauffer & Zuber 1998) similarly to *Pinus sibirica* in Siberia (Pavlov *et al.* 2023). This can lead to SP die-back, as currently reported from foresters in Styria. The fungal disease *Phacidium infestans* can be avoided through careful selection of the sites (micro-sites with shorter snowpack-duration) for SP cultivation (Ebner & Scherer 2001).

4.3 Economic use of Stone Pine products

Besides being beneficial for forest ecosystem resilience, cultivation of SP can be considered as economically attractive. The high economic value of SP is particularly highlighted by its timber prices. In fact, timber products (*e.g.* furniture produced from

SP timber) are highly demanded and obtain impressive prices. In Austria, for instance, two- to five-fold prices are reached for timber from SP compared to other conifers (Fig. 6). Additionally, the price for SP timber increased substantially during the last years, also in comparison to the timber prices of other conifer species in Austria according to the report of timber market in Tyrol (Fig. 6, Amt der Tiroler Landesregierung 2024), which is one of the sparse statistically relevant collection of revenues.

The high prices for SP timber may be explained by the aromatic scent and the high quality of SP lumber, it is lightweight, the knotholes are firmly interconnected with the surrounding lumber and it is easily workable. Due to this fact, "knottiness" is a desired qualitative aspect of SP timber (Langmaier 2013), which is in contrast to timber quality standards of other tree species. Additionally, a variety of non-wood forest products derived from SP are marketed, thus enhancing its economic use (Vacik *et al.* 2020). The essential oil of SP is one example obtained from the distillation of the branches and cones of this tree species, which is produced in Austria and Italy. The effect of the essential oil is described as relaxing, anxiety-relieving and calming (Czakert *et al.* 2024) and is often used in the wellness industry. It is applied in medicine, aromatherapy, local liquor production and in the fragrance industry (Chizzola 2021). Most of SP essential oil, which is rich in oxygenated terpenes, occurs in cones, with unripe cones delivering almost twice as much oil as ripe cones, whereas the wood only contains negligible amounts of the oil (Lis *et al.* 2017).

The flavonoid Pinocembrin was first detected in *Pinus cembra* and named accordingly (Erdtmann 1944). The essential oil of SP displayed high antimicrobial activity against the gram-positive bacteria *Sarcina lutea* and *Staphylococcus aureus* and the pathogenic yeast *Candida albicans* (Apetrei *et al.* 2013). It also showed bactericidal effects against other bacterial strains (Garzoli *et al.* 2021).

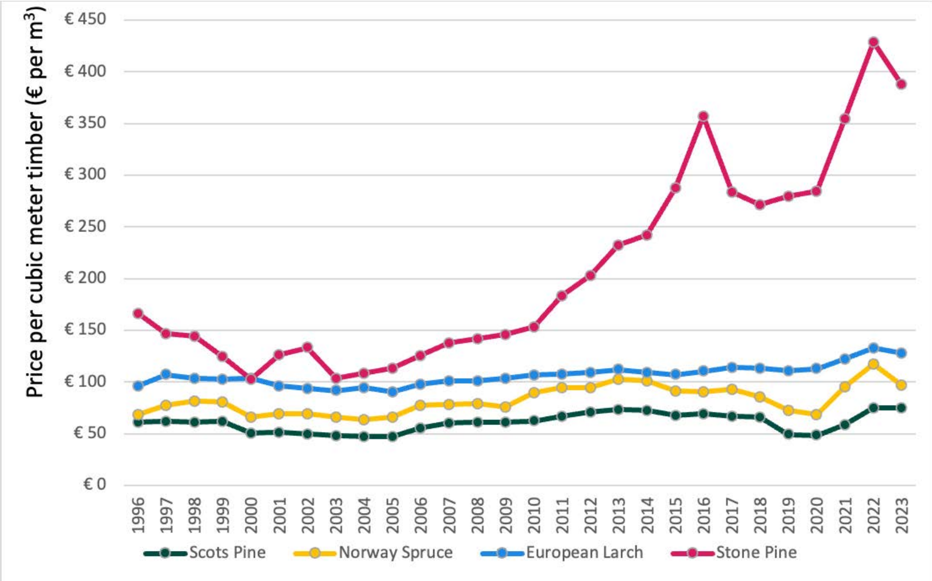

Figure 6: Development of timber prices per cubic meter (€ per m3) from 1996 to 2023 in the Austrian province Tyrol, compared between Stone Pine (Pinus cembra), Scots Pine (Pinus sylvestris), Norway Spruce (Picea abies) and European Larch (Larix decidua) (Amt der Tiroler Landesregierung 2024).

Abbildung 6: Entwicklung der Rohholzpreise per Festmeter (€ per m3) von 1996 bis 2023 im Bundesland Tirol, verglichen zwischen Zirbe (*Pinus cembra*), Waldkiefer (*Pinus sylvestris*), Gemeine Fichte (*Picea abies*) und Europäische Lärche (*Larix decidua*) (Amt der Tiroler Landesregierung 2024).

The cones of SP are also used for the production of liqueur, which is well renowned for its particular taste and used in many different forms. The seeds of SP are known for their delicious flavor and high nutritional value, being a rich source of proteins (17-18%), fats (50-59%) and carbohydrates (17%) (Mutke *et al.* 2013, Vacik *et al.* 2014). Essential minerals such as Zn, S, P, Na, Mn, Mg, K, Fe, and Ca were detected in Austrian samples of pine nuts (Kadim *et al.* 2023). The products derived from SP can therefore be assumed to have the potential to play a more important role in rural development, by generating socio-economic benefits to a range of actors along the entire value-chain spanning from the forest owner to the retailer who sells a product as a service to the final customer (Huber *et al.* 2019, Huber *et al.* 2023). This can lead to the development of new innovative business plans where more traditional, timber-production oriented forest management concepts can be integrated with non-wood forest products management, resulting in a co-production of forest products (Vacik *et al.* 2020).

5 Conclusions

The project 'Dynamic Forest Site Classification' (FORSITE), which was carried out between 2018 and 2023 in the Austrian province of Styria, created an empirical FSI plot data base. These data show that in the Austrian province of Styria the altitudinal range of forest stands with dominant and sub-dominant Stone Pine (SP) is broader than expected. FSI plots with SP occurrence were identified in six FVZ, spreading from 1250 m to 2050 m asl. The proportion of investigated FSI plots in the 'very cool' FVZ should be particularly highlighted, as for this FVZ the thermally more sensitive and demanding Silver Fir (*Abies alba*) is mentioned as characteristic tree species. The drivers for the presence of SP in forest stands of the three cool FVZ ('mco', 'co', 'vco') could have both agricultural and forest management origins and would need further investigations at local and regional level to identify the main causes. The agriculture-related driver is assumed to be associated with alpine pasture activities, which create rather open forest stands. This decreases competitive stress and facilitates the fungal species *Chrysomyxa rhododendri*, which occurs on *Rhododendron* species and infects Norway Spruce as an intermediate host and hence can diminish the competitive ability of this tree species. The driver related to forest management activities could be explained with the widespread afforestation of SP on forest areas which in the past were clear-cut for the production of charcoal used in blast furnaces for metal production. A differentiation of whether a forest stand with SP dominance was established by afforestation activities or by natural forest succession could not be carried out in the course of this study.

Our analysis indicates that SP could represent a viable option for silvicultural management within the upper six FVZ of Styria, where it can increase stability and resilience of the respective forest ecosystems and additionally contributes to the mitigation of climate change effects. In the lower situated FVZ like the 'moderately cool' and 'cool' zone, SP could be a valuable silvicultural alternative for the bark-beetle-threatened Norway Spruce, especially on forest sites with extremely low base saturation (base saturation class 'e'), where the set of suitable tree species is limited. On forest sites with high base saturation classes ('r' and 'm') the competitive force of Norway Spruce is high within the four lower situated FVZ, thus the cultivation of SP would require intensive silvicultural treatment (growing space regulation) at these forest sites. Within the uppermost two coldest FVZ ('cd' and 'vcd') SP represents a suitable tree species irrespective of the base saturation class of the soil and can be established either by natural regeneration or by afforestation.

As a result of the harsh climatic conditions at higher elevations, the vegetation responds to even slight climatic changes, which makes the timber line and tree line particularly suitable for monitoring the impacts of climate change (Marinov *et al.* 2015). In this context it would make sense to monitor the expected upward shift of the tree line as a result of the recent climate change. The change in area and the development of the SP stands at the tree line could be therefore a perfect indicator to monitor the climate change effect.

The economic value of SP should be highlighted as a potential incentive for forest owners to establish this tree species on their forest areas, as timber products of SP achieve high prices on the market and also non-wood forest products of SP, such as essential oils or liquors, represent an additional source of income long before harvesting.

Acknowledgements

The authors would like to thank the Province of Styria for the financial support of the project and the forest owners for making the research work possible and providing access to the survey plots. Such a comprehensive project can only be realized with the active support and commitment of numerous people and therefore we would like to thank all the teams involved in the field surveys and data analysis.

References

Ad-hoc-AG Boden (2005). Bodenkundliche Kartieranleitung, 5. Aufl. (KA5). E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart: 438 S.

Amt der Tiroler Landesregierung (2024). Mündliche Information, Landesforstdienst Tirol.

Apetrei, L. C., Spac, A., Brebu, M., Tuchilus, C., & Miron, A. (2013). Composition, antioxidant and antimicrobial activity of the essential oils of a full-grown tree of *Pinus cembra* L. from the Calimani mountains (Romania). Journal of the Serbian Chemical Society, 78(1), 27-37.

Badino, F., Ravazzi, C., Vall, F., Pini, R., Aceti, A., Brunetti, M., Champvillair, E., Maggi, V., Masper, F., Perego, R., Orombelli, G. (2018). 8800 years of high-altitude vegetation and climate history at the Rutor Glacier forefield, Italian Alps. Evidence of middle Holocene timberline rise and glacier contraction. Quaternary Science Reviews 185, 41-68.

BFW (2025). Bundesforschungszentrum für Wald - BFW – Österreichische Waldinventur/ Baumartenkarte, to be accessed via the homepage: https://www.waldinventur.at/?x=1486825&y=6059660&z=7.54947&r=0&l=1111#/map/1/mBaumartenkarte/Bundesland

Blum, W.E.H., Spiegel, H., Wenzel, W.W. (1989). Bodenzustandsinventur; Konzeption, Durchführung und Bewertung. Empfehlungen zur Vereinheitlichung der Vorgangsweise in Österreich. Arge Bodenzustandsinventur d. Österr. Bodenkundl. Gesellschaft; Bundesministerium für Land- und Forstwirtschaft, Wien, 95 pp.

Brandstätter, J., Wagner, T., Stüwe, K., Wilhelmy, M. , Winkler, G. (2023). Die Geologie in der Steiermark. In: Amt der Steiermärkischen Landesregierung, Dynamische Waldtypisierung Steiermark, 2023, p. 34-43.

Braun-Blanquet, J. (1964). Pflanzensoziologie. Grundzüge der Vegetationskunde. 3. Auflage, Springer-Verlag, Wien.

Carli, A. (2014). Die Lärchen-Zirbenwälder im Nationalpark Gesäuse sowie pflanzensoziologische Diskussion des Carbonat-Lärchen-Zirbenwaldes in Österreich. Bericht – Nationalpark Gesäuse GmbH, Steiermark.

Caudullo, G., Welk, E., San-Miguel-Ayanz, J. (2017). Chorological maps for the main European woody species. Data in Brief 12, 662-666.

Chizzola, R., Billiani, F., Singer, S., & Novak, J. (2021). Diversity of essential oils and the respective hydrolates obtained from three *Pinus cembra* populations in the Austrian Alps. Applied Sciences, 11(12), 5686.

Czakert, J., Kandil, F.I., Boujnah, H. et al. (2024). Scenting serenity: influence of essential-oil vaporization on dental anxiety - a cluster-randomized, controlled, single-blinded study (AROMA_dent). Sci Rep 14, 14143 (2024). DOI: 10.1038/s41598-024-63657-w

Ebner, S., Scherer, A. (2001). Die wichtigsten Forstschädlinge: Insekten, Pilze, Kleinsäuger. (5-te Auflage, ed Praxisbuch).

Ellenberg, H., Weber, H. E., Düll, R., Wirth, V., Werner, W., Paulißen, D. (1992). Zeigerwerte der Pflanzen in Mitteleuropa. Scripta Geobotanica 18, Goltze-Verlag Göttingen, 1-258.

Englisch, M., Gadermaier, J., Katzensteiner, K., Keßler, D., Klosterhuber, R., Koeck, R., Schaufler, J., Starlinger, F. (2023). Standortsklassifikation. In: Dynamische Waldtypisierung Steiermark, Band 1. Editiert von Roland Koeck und Harald Vacik. Amt der Steiermärkischen Landesregierung, Graz.

Erdtman H. (1944). Die phenolischen Inhaltsstoffe des Kiefernholzes VI. Das Kernholz von *Pinus cembra* L. Svensk Kem Tid, 56: 26–31.

Formayer, H., Clementschitsch, L., Hofstätter, M., Kromp-Kolb, H. (2009). Vor Sicht Klima! Klimawandel in Österreich, regional betrachtet (Endbericht Global 2000, Mai 2008). BOKU-Met Report 16, ISSN 1994-4179 (Print), ISSN 1994-4187 (Online). Access via: http://www.boku.ac.at/met/report/BOKU-Met_Report_16_online.pdf

Garzoli, S., Masci V. L., Caradonna V., Tiezzi A., Giacomello P., Ovidi E. (2021). Liquid and Vapor Phase of Four Conifer-Derived Essential Oils: Comparison of Chemical Compositions and Antimicrobial and Antioxidant Properties. Pharmaceuticals. 2021; 14(2):134. DOI: 10.3390/ph14020134

Grote, V., Frühwirth, M., Lackner, H. K., Goswami, N., Köstenberger, M., Likar, R., Moser, M. (2021). Cardiorespiratory interaction and autonomic sleep quality improve during sleep in beds made from *Pinus cembra* (stone pine) solid wood. International Journal of Environmental Research and Public Health, 18(18), 9749. DOI: 10.3390/ijerph18189749,

Gugerli F., Brodbeck, S., Bebi, P., Bollmann, K., Dauphin, B., Gossner, M., Krumm, F., Peter, M., Queloz, V., Reiss, G., Rellstab, C., Stofer, S., von Arx, G., Wasem, U., Zweifel R. (2022). Die Arve – Portrait eines Gebirgswaldbaums. WSL Merkbl. Prax. 72. 16 S.

Hättenschwiler, S., Körner, C. (1995). Responses to recent climate warming of *Pinus sylvestris* and *Pinus cembra* within their montane transition zone in the Swiss Alps. Journal of Vegetation Science 6: 357-368.

Huber, P., Kurttila, M., Hujala, T., Wolfslehner, B., Sanchez-Gonzalez, M., Pasalodos-Tato, M., de-Miguel, S., Bonet, J.A., Marques, M., Borges, J.G., Enescu, C.M., Dinca, L., Vacik, H. (2023). Expert-Based Assessment of the Potential of Non-Wood Forest Products to Diversify Forest Bioeconomy in Six European Regions. FORESTS. 2023; 14(2), 420.

Huber, P., Hujala, T., Kurttila, M., Wolfslehner, B., Vacik, H. (2019). Application of multi criteria analysis methods for a participatory assessment of non-wood forest products in two European case studies. FOREST POLICY ECON. 103: 103-111.

Jandl, N., Jandl, R., Schindlbacher, A. (2018). Future management options for cembran pine forests close to the alpine timberline. Annals of Forest Science 75: 81.

Johann, E. (2021). Die forstliche Geschichte des Bezirkes Murau. Teilkapitel in: WEP Murau (2021). Waldentwicklungsplan, politischer Bezirk Murau, 2. Revision. Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft, Wien.

Kadim, S., Al-Taee, M., Radhi, H., Dham, A., Talib Kareem, A., Abbas, A.H., Abid, M. (2023). Mineral Profiling of Various Pine Nut Species Cultivated in Egypt. Journal of Nuts, 14(4), 239-250. DOI: 10.22034/jon.2023.1978790.1209

Kilian W. (2015). Schlüssel zur Bestimmung der Böden Österreichs. 2. Aktualisierte Auflage Mitt. Österr. Bodenkundl. Ges., Wien, 81. 74 S.

Kirisits, T., Cech, T.L. (2007). Auffälliges Vorkommen der *Dothistroma*-Nadelbräune an Zirben im oberen Murtal. Forstschutz Aktuell 41, pp. 14-15.

Kölling, C., Hoffmann, M., Gulder, H. J. (1996). Bodenchemische Vertikalgradienten als charakteristische Zustandsgrößen von Waldökosystemen. Zeitschrift für Pflanzenernährung und Bodenkunde 159, S. 69–77.

Körner, C. (1998). A re-assessment of high elevation tree line positions and their explanation. Oecologia 115, 445 – 459.

Körner, C. (2003). Alpine plant life. Functional plant ecology of high mountain ecosystems. Springer Verlag, Berlin.

Landesforstdirektion Steiermark (2023). FORSITE - Standort – Steiermark. Groups of main forest sites defined by a characteristic tree species composition; forest vegetation zones with zonal forest groups and special forest site units with abnormal site conditions. https://data.steiermark.at/cms/beitrag/11822084/97108894/?AppInt_OGD_ID=1467.

Langmaier, M. (2013). Qualitätsmerkmale (Astigkeit) der Zirbe in Abhängigkeit von Bestandesalter und -struktur. Diplomarbeit am Institut für Waldbau, Universität für Bodenkultur, Wien, pp 91.

Langmaier, M., Hochbichler, E. (2015). Strukturanalyse von Karbonat Lärchen-Zirben-Wäldern im Nationalpark Gesäuse. Endbericht, Nationalpark Gesäuse GmbH, Steiermark.

Lehner, F., Formayer, H. (2023). Klima der Steiermark. In: Amt der Steiermärkischen Landesregierung, Dynamische Waldtypisierung Steiermark, 2023, p. 44-55.

Lehner, F., Maier, P., Klisho, T., & Formayer, H. (2024a). FORSITE-Clim Europe: European-wide climate indicators for historical periods and climate projections at high resolution [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10623854.

Lehner, F., Klisho, T., & Formayer, H. (2024b). BioClim Austria: Gridded climate indicators for 1961-1990 and 1991-2020 at 250m resolution [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10887293.

Lick, H. (1991). Das Wachstum der Zirbe bei Murau. Diplomarbeit, Institut für Forstliche Ertragslehre, Universität für Bodenkultur, Wien.

Lis, A., Kalinowska, A., Krajewska, A., & Mellor, K. (2017). Chemical composition of the essential oils from different morphological parts of *Pinus cembra* L. Chemistry & Biodiversity, 14(4), e1600345.

Liu, Y., Goodrick, S., Williams, M., Zhang, A. (2024). Climate change and variability overview. In: Future Forests – Mitigation and Adaptation to Climate Change. Elsevier, p. 7-48. https://doi.org/10.1016/B978-0-323-90430-8.00010-1

Mayer, H. (1974). Wälder des Ostalpenraumes. Gustav Fischer Verlag, New York.

Mayer, H. (1992). Waldbau auf soziologisch-ökologischer Grundlage. Gustav Fischer Verlag, New York, pp 521.

Marinov, I., Popov, G., Pandeva, D., Bobeva, A. (2015). Upper forest limit – ecological role and protection, "Gora" Magazine, 5/2015, Bulgaria.

Mucina, L., Grabherr, G., Wallnöfer, S. (1993). Die Pflanzengesellschaften Österreichs. Teil III – Wälder und Gebüsche. Gustav Fischer Verlag, Jena – Stuttgart – New York.

Mutke S., Pastor A., Picardo A. (2013). Toward a traceability of European pine nuts \"from forest to fork\". In: Mutke S. (ed.), Piqué M. (ed.), Calama R. (ed.). Mediterranean stone pine for agroforestry. Zaragoza: CIHEAM / FAO / INIA / IRTA / CESEFOR / CTFC, 2013. p. 105-109 (Options Méditerranéennes: Série A. Séminaires Méditerranéens; n. 105)

Nagavciuc, V., Kern, Z., Ionita, M., Hartl, C., Konter, O., Esper, J. Poper, I. (2020). Climate signals in carbon and oxygen isotope ratios of *Pinus cembra* tree-ring cellulose from the Calimani Mountains, Romania. International Journal of Climatology 40, 2539-2556.

Nestroy, O., Aust, G., Blum, W.E.H., Englisch, M., Hager, H., Herzberger, E., Kilian, W., Nelhiebel, P., Ortner, G., Pecina, E., Pehamberger, A., Schneider, W., Wagner, J. (2011). Systematische Gliederung der Böden Österreichs - Österreichische Bodensystematik 2000 in der revidierten Fassung von 2011. Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft, Heft 79, Wien.

Neuschulz, E.L., Merges, D., Bollmann, K., Gugerli, F., Böhning-Gaese, K. (2018). Biotic interactions and seed deposition rather than abiotic factors determine recruitment at elevational range limits of an alpine tree. Journal of Ecology 106, 948-959.

Oberhuber, W., Thomaser, G., Mayer, S., Bauer, H. (1999). Radial growth of Norway spruce affected by *Chrysomyxa rhododendri*. Phyton – Annales Rei Botanicae 39(4), 147-154.

Pavlov, I.N., Vasaitis, R., Litovka, Y.A., Timofeev, A.A., Menkis, A. (2023). Infestation by *Ips amitinus* (Eichhoff, 1872), Its Associated Fungi, and Butt Rots in Stands of *Pinus sibirica* in South-Western Siberia. Forests 14 (2383), pp. 14.

Popa, I., Nechita, C., Hofgaard, A. (2017). Stand structure, recruitment and growth dynamics in mixed subalpine spruce and Swiss stone pine forests in the Eastern Carpathians. Science of the Total Environment 598, 1050–1057.

Schütt, P., Weisgerber, H., Schuck, H.J., Lang, U., Stimm, Roloff, H. (2008). Lexikon der Nadelbäume. Wiley-VCH Verlag – Nikol Verlagsgesellschaft, pp 640.

Simon, A., Wilhelmy, M., Klosterhuber, R., Cocuzza, E., Geitner, C., Katzensteiner, K. (2021). A system for classifying subsolum geological substrates as a basis for describing soil formation, CATENA, Volume 198, 2021, 105026, ISSN 0341-8162.

Stauffer, C., Zuber, M. (1998). *Ips amitinus* var. *montana* (Coleoptera, Scolytidae) is synonymous to *Ips amitinus*: a morphological, behavioural and genetic re-examination. Biochemical Systematics and Ecology 26 (1998) 171-183.

Ulber, M., Gugerli, F., Bozic, G. (2004). EUFORGEN - Technical Guidelines for genetic conservation and use for Swiss stone pine (*Pinus cembra*). International Plant Genetic Resources Institute, Rome, Italy. 6 pp.

Vacik, H., Hale, M., Spiecker, H., Pettenella, D., Tomé, M. (2020). Non-Wood Forest Products in Europe, Ecology and management of mushrooms, tree products, understory plants and animal products. Outcomes of the COST Action FP1203 on European NWFPs, 416, BoD, Norderstedt;

Vacik, H., Wolfslehner, B., Huber, P., Ruprecht, H. (2014). Analysis of Non Wood Forest Products and Forest Services in Sustainable Forest Management. AUSTRIAN J FOR SCI. 2014; 131(3): 147-169.

Wilhelmy, M. (2021). Classification of subsolum geological substrates (SGS) as basis for soil formation and area covering data about nutrients potential and water balance. Presentation, Eurosoil 2021, Geneva, Switzerland.

Willner, W., Grabherr, G. (2007). Die Wälder und Gebüsche Österreichs. Elsevier – Spektrum, Akademischer Verlag, Heidelberg.

Zieba, A., Rozanski, W., Szwagrzyk, J. (2020). Structure of dominance among tree species in relic Swiss stone pine (*Pinus cembra* L.) forests in Tatra Mountains. Pol. J. Ecol. 68, 159-171.