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Identifying suitable areas for plenter forest management

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ABSTRACT

Plenter forests, also known as uneven-aged or continuous cover forests enhance forest resilience and resistance against disturbances compared to even-aged forests. They are considered as an adaptation option to mitigate climate change effects. In this study, we present a conceptual approach to determine the potentially suitable area for plenter forest management within central European mixed species forests and apply our approach to the case study area in Styria, the south-eastern Province of Austria. The concept is based on ecological and technical-economic constraints and considers expected future climate conditions and its impact on plenter forest management. For each 1 ha forest pixel, we assess the ecological conditions for plenter forest management according to the autecological growth conditions of silver fir, and at least one additional shade tolerant tree species. The technical-economic constraints are defined by slope ($\leq$30%) and distance to the next forest road ($\leq$100 m) to ensure cost-efficient harvesting. The results show that under current climate conditions 28.1% or 305,349 ha of the forests in Styria are potentially suitable for plenter forest management. For the years 2071–2100 and under the climate change scenario RCP 4.5, the potential area decreases to 286,098 ha (26.3% of the total forest area) and for the scenario RCP 8.5 to 208,421 ha (19.1% of the total forest area). The main reason for these changes is the unfavourable growing conditions for silver fir in the lowlands, while in the higher elevations silver fir is likely to expand. Our results may serve forest managers to identify areas suitable for plenter forests and assist in the transformation of even-aged pure forests to uneven-aged forests to increase resistance, resilience, and biodiversity under climate change.

1. Introduction

With the increasing impacts of climate change, the need for resilient and resistant forests to ensure the maintenance of ecosystem services such as timber production, biodiversity, protection of infrastructure, and carbon storage is of growing interest (European Commission, 2021; Lackner et al., 2023; Larsen et al., 2022). In the past, even-aged pure forests were promoted for their economic benefits (Mason et al., 2021; Puettmann et al., 2015; Spiecker et al., 1996). These stands are now increasingly affected by biotic and abiotic disturbances (Dvorak et al., 2001; Jandl, 2020; Lackner et al., 2023; Mohr et al., 2024; Seidl et al., 2011).

One option to adapt forest management to changing growing conditions is to transform these even-aged pure forest stands into uneven-aged, mixed-species stands (Brang et al., 2014; Forest Europe, 2020; Hasenauer, 2006; Larsen et al., 2022; Puettmann et al., 2015), since studies have shown that structurally diverse mixed forests enhance stability as well as resilience and enrich biodiversity (Brang et al., 2014; Griess et al., 2012; Heidrich et al., 2023; Mohr et al., 2024; Schütz, 2001), while the economic productivity remains high (Knoke, 2009; Schütz, 2001; Uhl et al., 2021).

Uneven-aged, mixed-species management semi-synonymously called plenter forest management, continuous cover forestry, or "Dauerwald" (Pommerening, 2024; Pommerening and Murphy, 2004; Schütz et al., 2012) maintains a constant crown cover by preserving a multi-storied forest structure, resulting in a diverse size and age structure. These semi-synonymously used silvicultural terms may imply different things. For example, Dauerwald (Möller, 1922) is used to describe forest management systems that are avoid clear-cuts and promote natural regeneration (Pukkala, 2016). The comparable English term for Dauerwald is "continuous cover forestry", which underlines three principles in forest management: (i) continuous cover, (ii) stand stability, and (iii)

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naturalness (Davies et al., 2008; Schütz et al., 2012). Plenter forest management is a special form of Dauerwald aiming for a pre-defined and steady forest structure, which requires regular harvests (Pukkala, 2016; Schütz, 1992, 1994).

In this study, we focus on plenter forests in a strict sense ("Einzelplenterwald", see Schütz (1992)), namely conifer dominated, naturally regenerating stands that are managed by single-tree harvesting, resulting in economically profitable plenter forests (see Forrester et al., 2022; Leibundgut, 1979; Schütz, 1992, 2001; Schütz et al., 2012). In such single-tree-use plenter forests, the ratio of beech is kept low for economic reasons (Schütz, 1992) because conifers trees maintain a smaller crown, which allows a higher number of larger trees per unit area versus broad-leaf dominated stands (Schütz et al., 2012). In these plenter forests, gaps for natural regeneration are created by harvesting single trees, not before they reach a pre-defined diameter or show signs of reducing growth. Smaller trees have to survive with limited light availability and "wait" for canopy openings through harvesting (Golser and Hasenauer, 1997; Mitscherlich, 1952; Schütz, 2001; Thurnher et al., 2011). Thus, plenter forest management favours shade tolerant tree species, while clear-cut management promotes light-demanding species (Cameron and Alexander, 2023; Käber et al., 2021; Klopčič et al., 2015; Leibundgut, 1946; Schütz, 2001).

The suitability of different tree species for plenter forest management has been widely debated in the literature (Ammon, 1937; Leibundgut, 1946; Nicolescu et al., 2023; Reininger, 2000; Schütz, 2001; Zingg et al., 2009). Ammon (1937) argued that all species which regenerate naturally may be managed as plenter forests. Leibundgut (1946) and Mitscherlich (1952) questioned the long-term suitability of light demanding species in plenter forests. Schütz (2001) concluded that only tree species with high shade tolerance during their juvenile phase should be considered for plenter forest management, as they need to survive long periods with minimal light. According to Leibundgut (1945) and Schütz (1994, 2001), areas with favourable growth conditions for silver fir (*Abies alba* Mill.) are potentially suitable for plenter forest management. Zingg et al. (2009) argued that while all tree species can potentially be used in plenter systems by manipulating the light regime within the stand according to the species' needs, the economic feasibility of using species other than fir, spruce, and beech—whose economic performance in plenter forests is well-documented—remains insufficiently studied. Burschel and Huss (1997) identified the broadleaved species European beech (*Fagus sylvatica* L.), hornbeam (*Carpinus betulus* L.), sycamore maple (*Acer pseudoplatanus* L.), and large-leaf linden (*Tilia platyphyllos* Scop.) as well as the coniferous species Norway spruce (*Picea abies* (L.) H. Karst.) and Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) as shade to moderately shade tolerant species. The admixture of one or more of those species with silver fir can form uneven-aged mixed plenter forests, if appropriate silvicultural management is applied (Boncina et al., 2014; Forrester et al., 2021; Frei et al., 2022; Hein et al., 2009; Nicolescu et al., 2023; Radoglou et al., 2009).

In Central and Eastern Europe, typical plenter forests are commonly found in mixed species forest ecosystems growing in the Alps, the Carpathians, the Dinarides, and the Rhodopes, at an elevation from 600 to 1,400 m. These forests include a mix of silver fir (*Abies alba* Mill.), Norway spruce (*Picea abies* (L.) H. Karst.), and European beech (*Fagus sylvatica* L.) and often some of the above-mentioned shade to semi-shade tolerant species (Ambs et al., 2024; Boncina, 2011; Čilaš et al., 2023; Forrester et al., 2022; Keren et al., 2017; Leibundgut, 1946; Mitscherlich, 1952; Ralhan et al., 2024; Reininger, 2000; Schütz, 2001; Uhl et al., 2021).

Plenter forest management may also take place in a more general sense ("Gruppenplenterung", see Schütz (1992)), requiring larger regeneration gaps created by harvesting "tree groups", e.g., in beech forests even though beech tends to form pure (Hessenmöller et al., 2012) and uniform stands (Hessenmöller et al., 2018; Schütz, 2001). Similarly, pure Norway spruce plenter forests may be found in subalpine areas (Indermühle, 1978) or boreal forests (Kuuluvainen et al., 2012), but they require "group harvest" management, to maintain a heterogenous structure (Uhl et al., 2021). This also applies to oak: Harvesting "tree groups" reduces the basal area within oak stands, initiates regeneration and promotes structured oak forests (Schütz, 1992; Schütz et al., 2016).

Mixed fir, spruce, and beech plenter forests allow a higher growing stock to maintain the typical uneven-aged mixes species stand structure (Leibundgut, 1979; Schütz, 1992; Schütz et al., 2012), while pine species (*Pinus* spp.) and European larch (*Larix decidua* Mill.) are light demanding pioneer species which make the maintenance of a plenter forest structure difficult or even impossible (Guldin et al., 2017; Pommerening, 2024; Reininger, 2000). In this study we focus on uneven-aged mixed species management with regular single tree harvesting, as the separation of typical plenter forest management from similar management forms such as shelterwood cuttings (Leibundgut, 1979; Schütz, 1992) is often difficult.

The transition towards plenter forest management introduces new challenges for forest managers (Puettmann et al., 2015). It requires a re-evaluation of sustainability indicators (O'Hara et al., 2007), modifications of forest inventory designs (Dvorak, 2000; Leiter and Hasenauer, 2023), adaptation of yield predictions (Čilaš et al., 2023; Dvorak, 2000; Hasenauer, 2006; Thurnher et al., 2011), adjustments of production cycles (Reininger, 2000; Schütz, 2001), and professional training for forest managers (Puettmann et al., 2015; Pommerening, 2024).

From a forest engineering perspective, plenter management leads to larger-sized logs, compared to age-class forests (Bacher, 2003; Knežević et al., 2023; Puettmann et al., 2015; Reininger, 2000) which in turn may modify the harvesting system (Bacher, 2003; Pausch, 2005). Furthermore, plenter forest management increases the frequency of harvesting operations while the intensity per harvesting operation decreases. This requires low-impact harvesting to avoid any damage to the remaining stand and the regeneration (Larsen et al., 2022; Nill, 2011; Puettmann et al., 2015). Thus, a dense road network system is needed to extract the harvested trees using skidders or tractors equipped with cable winches (Berendt et al., 2017; Knežević et al., 2023). According to the latest European forestry report, about 25% of Europe's forests are managed as uneven-aged or continuous cover forest (Forest Europe, 2020), but little is known about the area where this management method could be applied in the future.

The purpose of this study is to introduce a new approach to identify the potentially suitable areas for plenter forest management. As a case study for demonstrating our approach, we selected the forests of the province of Styria, Austria, covering about 1.09 million hectares or 61.8% of the province's land area (BFW, 2022). The forests cover a large gradient in elevation ranging from 300 to 2,200 m, and grow on various geological zones (sandy soils, flysch, greywacke, and limestone) resulting in a wide variety of forest mixture types. Due to historic land use impacts, pure even-aged Norway spruce stands managed in a clear-cut system with a strong focus on timber production are dominating (BFW, 2022; Federal Ministry of Agriculture, Forestry, Regions and Water Management, 2022). The current share of multi-storied plenter forests (Gabler and Schadauer, 2008) in Styria is estimated at 6.3% of the forest area and has more than doubled since 1996 (BFW, 2022). However, the locations of potential new sites for plenter forest management are unknown, making it difficult for forest managers to decide whether to transform their forests into plenter forests. The objective of this study is to identify suitable plenter forest areas within the case study area of Styria, Austria, based on the ideas of ecological and technical-economic limitations for plenter forest management (see Mason et al., 2021; Puettmann et al., 2015).

To achieve this, the study includes.

(i) an assessment of regional potential tree species suitability in forming uneven-aged, mixed species plenter forests,
(ii) an analysis of the technical and economic constraints for plenter forest management, and

(iii) an evaluation of the expected future shifts in the forest area potentially suitable for plenter forest management under two climate change scenarios (RCP 4.5 and RCP 8.5).

2. Materials and methods

Plenter forest management needs a minimal stand size of 1 ha to ensure that all development stages of trees can coexist (Schütz, 2001). Thus, we chose a resolution of 100 m × 100 m (1 ha) and assume that all forested 1 ha pixels are potentially suitable for plenter forest management. Next, we analyse the ecological and technical-economic conditions by 1 ha pixel according to the following three factors: (i) suitability of tree species, (ii) the slope of the terrain, and (iii) the distance to the next road. The first factor addresses the ecological constraints for plenter forest management, while the two remaining factors cover the technical-economic limitations for plenter forest management to areas where cost-efficient ground-based skidding is possible.

2.1. Ecological limitations

A plenter forest site should support the growth of silver fir (Leibundgut, 1945; Schütz, 2001) and an additional shade tolerant species (Burschel and Huss, 1997) to allow a species mixture leading to a higher biodiversity, resilience, and resistance versus pure forests (Brang et al., 2014; Uhl et al., 2021).

In our study, we follow the concept of ecological limitations for potential plenter forest management. The concept is based on the autecological suitability of tree species as implemented in an expert model (Fig. 1) developed by Steiner and Lexer (1998), Lexer and Hönninger (1998a, 1998b), Pichler (2000), Kessler and Lexer (2022a, 2022b), Kessler et al. (2022), and Kessler et al. (2024). The approach integrates the ecophysiological characteristics of tree species, i.e. demand and tolerance to the site factors (i) nutrients and (ii) water supply, (iii) thermal conditions as well as (iv) risk and predisposition factors (Fig. 1).

In the model, nutrient supply is defined by (i) the nutrient adsorption potential of the soil, (ii) the nutrient concentration of the soil, (iii) the chemical conditions for plant availability of the nutrients, and (iv) the root penetration potential of the soil. The nutrient adsorption potential is represented by the physical components soil depth, coarse fraction, soil texture, and organic carbon content. The nutrient concentration results from the base saturation of the soil, whereas the chemical conditions for plant availability of the nutrients come from the soil pH. The root penetration potential of the soil integrates the limiting effect of heavy soils, high shares of coarse material as well as groundwater and waterlogging (Steiner and Lexer, 1998; Kessler et al., 2024).

Water available from precipitation is represented by a soil moisture index which is defined as the possible supply of water to satisfy the potential evapotranspiration. The total water supply for a given environment results from the combination of (i) the soil moisture index and (ii) the water supply by groundwater. For further details, we refer to Steiner and Lexer (1998).

The thermal conditions are defined by the limiting effect of winter frost and late frost, the length of the vegetation period as well as by a combination of the growing degree days (heat sum above a threshold of 5 °C), and the limitation of net primary production by heat (Steiner and Lexer, 1998; Kessler et al., 2024).

Recently, a risk assessment module has been included in the approach (see Kessler and Lexer, 2022b; Kessler et al., 2024) which considers the frequency of drought years (i.e. years with dry spells) as well as the predisposition for windthrow. A drought year is defined as a year in which the soil moisture index of the driest month during the vegetation period exceeds the tolerance limit of a given species. The predisposition for windthrow is defined by a combination of the potential rooting depth and the root penetration potential of a species. For Norway spruce, risk from the spruce bark beetle (*Ips typographus*) is included as well.

The ecological drivers including the required spatial input information for the model are shown in Table 1. For a given site, tree species-specific monocausal responses are calculated for each individual soil and climate input parameter by assigning a response value ranging from 0 (unsuitable) to 1 (highly suitable) according to species-specific response functions and matrices (Steiner and Lexer, 1998). The response functions and matrices were parametrized with empirical data, available literature, and expert knowledge.

For calculating the final autecological tree species suitability, the species-specific monocausal response values (i.e. suitability) which address individual soil and climate parameters (Fig. 1, Table 1) are combined according to rules and mathematical operators representing the following ecological interrelationships among the individual responses (Steiner and Lexer, 1998): (i) limitation (e.g. selection of lowest monocausal response by minimum-operator), (ii) compensation (e.g.

Table 1
Summary of the soil and climate input data by site factor required to run the tree species suitability model. The Soil Moisture Index indicates the coverage of potential evapotranspiration by soil water. Note that the risk of bark beetle infestations is only addressed for *Picea abies*.

Site factor	Soil/climate parameter
Nutrient supply	soil depth, coarse fraction, soil texture, organic carbon content, base saturation, pH, waterlogging, groundwater
Water supply	Soil Moisture Index, groundwater
Thermal conditions	Winter frost, late frost, budburst date, growing degree days >5 °C, heat, length of vegetation period
Predisposition against flooding	Flooding
Predisposition against windfall	Soil depth, coarse fraction, soil texture, waterlogging, groundwater
Risk of dry periods	Number of years per decade with dry periods
Risk of bark beetle infestation	Number of years per decade with ≥2 generations of *Ips typographus*

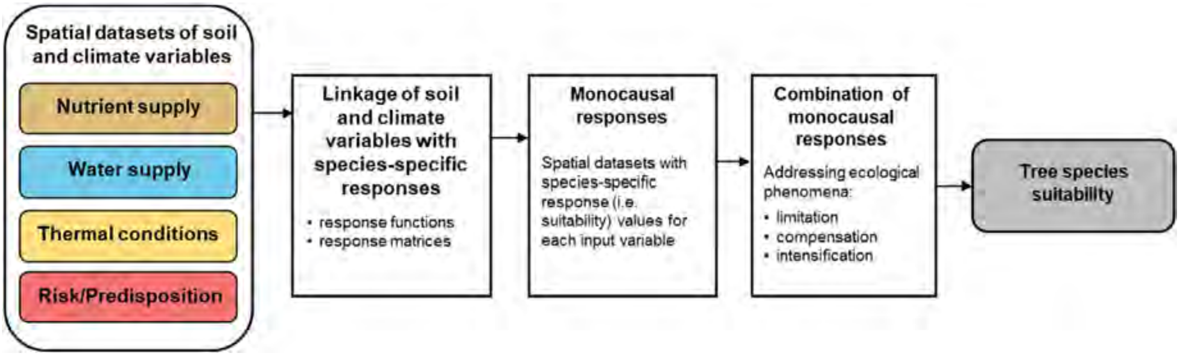

Fig. 1. Conceptual overview of the expert model applied to assess the autecological tree species suitability as indicator for the ecological limitation for potential plenter forest management area.

geometric mean of monocausal responses), (iii) intensification (e.g. multiplication of monocausal responses).

The aggregation of the individual response values is implemented in a hierarchical framework which first combine the monocausal responses within the ecological factor groups (i.e. nutrient supply, water supply, thermal conditions, risk), followed by a combination of the aggregated response values in the factor groups nutrient and water supply, thermal conditions, and finally risk. The conceptual approach of the mathematical operators is given in Steiner and Lexer (1998) and the integration of the soil and climate parameters within the suitability model (Table 1) in Kessler and Lexer (2022b).

The expert model (Fig. 1) uses spatially explicit information of individual site parameters as input data (see also section 2.3.2. and section 2.3.3.) to generate spatially explicit tree species suitability maps at a 100 m × 100 m (=1 ha) resolution. The resulting maps show raster cells with a high suitability for silver fir (each raster cell requires a minimum suitability value of 0.8) and a moderate suitability (suitability value between 0.5 and 0.8) of at least one of the following shade-tolerant tree species: European beech, Norway spruce, Douglas fir, hornbeam, sycamore maple or largeleaf linden. The thresholds of the suitability classification (e.g. high, moderate) follow the suggestion by Vacik et al. (2022).

During the application of the expert model for the two climate change scenarios RCP 4.5 and RCP 8.5 (Lehner et al., 2024), the thermal conditions, water supply and risks (e.g. drought periods) are updated according to the climate scenario, while the nutrient supply remains constant. The current climate is defined by the average data for the period 1989 to 2018 (Lehner et al., 2024).

2.2. *Technical-economic limitations*

Plenter forests require specific harvesting conditions, as the harvesting scale changes from a stand level to a single tree (or small-scale group), leading to more frequent but less intensive harvesting operations versus even-aged forests. This makes the use of cable yarding systems very costly (Pausch, 2005) and limits areas for cost-efficient plenter management to areas where ground-based harvesting methods are applicable. Only on slopes ≤30%, ground-based harvesting methods such as fully mechanized harvest with harvester and forwarder or partly mechanized harvest with chainsaw and tractors with cable winches are possible (Kühmaier and Stampfer, 2010).

Although fully mechanized harvesting would be even more cost-efficient, partly mechanized, low-impact harvesting with chainsaw and tractors is preferred in plenter forests. Low-impact harvesting avoids heavy machinery and reduces damage to the regeneration and the remaining stand (Berendt et al., 2017; Knežević et al., 2023). Using tractors equipped with cable winches, the maximum efficient extraction distances without leaving the forest road is up to 100 m (Kühmaier and Stampfer, 2010). Thus, a high-density road network, which allows for regular access to the plenter forest stand and shorter skidding distances (Nill, 2011), is another key factor for plenter management. Forests with no or only limited road access are considered to be unsuitable for plenter forest management. Consequently, economically feasible plenter forest management is limited to forest sites where (i) ground-based harvesting is possible (slope ≤30%), and (ii) a dense road network exists resulting in a skidding distance of ≤100 m.

2.3. *Data*

2.3.1. *Study area*

Our study covers the forest area in Styria, a southern province of Austria, characterized by a topographic gradient ranging from 200 m in the lowlands of the southeast to 2,800 m in the Alpine region of the northern and western part of the province. The climatic gradient follows the topography and exhibits an annual mean temperature of 6.73 ± 2.37 °C and precipitations of 1,097 ± 296 mm (Land Steiermark, 2021).

Forests cover 61.8% or 1.09 million ha of Styria's land area, making it the Austrian province with the highest forest share. The northern part of Styria belongs to the “Northern Limestone Alps”, with carbonate bedrock and a forest area of 188,411 ha or 17.35%. The south-eastern area of Styria consists mainly of siliceous bedrock and covers a forest area of 897,724 ha or 82.65%.

Since we are interested in potential differences of elevation and bedrock classes, we divided the forest area by siliceous and carbonate soils (Englisch et al., 2022). Additionally, each bedrock cluster is split into three elevation groups (low, middle, and high). On carbonate sites the elevation group *low* covers all sites <600 m, *middle* 600 to 1,400 m and group *high* > 1,400 m in elevation. On siliceous sites, the *low* elevation sites are <700 m, *middle* between 700 and 1,500 m and *high* elevation sites are >1,500 m (Kilian et al., 1994). These groups exhibit similar soil properties and climatic conditions, resulting in a similar potential species mixture, which is expected to have a strong impact on the suitability for potential plenter forest management.

The forest coverage of Styria was obtained from a map produced by the Austrian Research Centre for Forests (BFW, 2023). The statistical software R (R Core Team, 2023) and ArcGIS were used to run the analysis. Fig. 2 provides an overview of the study area.

2.3.2. *Tree species suitability data*

Data on the current and future tree species suitability, available at a 30 m × 30 m resolution, are provided by the Provincial Government of Styria (Land Steiermark, 2023a). For this study, we re-calibrated the tree species suitability data at 100 m × 100 m, as 1 ha is the minimum size for plenter forest management (Schütz, 2001). The data for evaluating the autecological suitability of a tree species on a given site (see Table 1), such as soil (Land Steiermark, 2023b), nutrient supply (Land Steiermark, 2023c) and climate (Land Steiermark, 2021) are also provided by the Provincial Government of Styria. For further information on the soil and nutrient supply data as well as the climate data, we refer to Hiebl and Frei (2016, 2018), Land Steiermark (2021), Lehner and Formayer (2022), and Lehner et al. (2024).

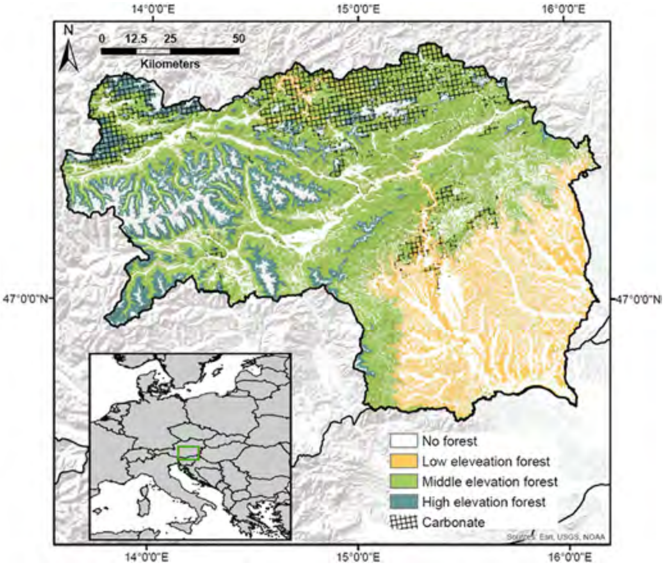

Fig. 2. Overview of the study area, Styria, the south-eastern province of Austria with a forest cover of 68% (1.09 mill. ha) of the land area and a large gradient in elevation. In the northern part of the province the bedrock consists of carbonate while most of the remaining part is siliceous bedrock.

For deriving the tree species suitability under future climate (the 30-year average of the period 2071–2100), and the climate change scenarios, the Representative Concentration Pathway (RCP) 4.5 as well as RCP 8.5, are obtained. The values 4.5 and 8.5 indicate a positive change in radiative forcing of 4.5 and 8.5 $W\cdot m^{-2}$ compared to the historic climate data (IPCC, 2021).

2.3.3. *Digital elevation data*

A detailed digital elevation model (DEM) of Styria at 10-m resolution comes from the Provincial Government of Styria (Land Steiermark, 2010) and is freely available. It is based on airborne laser scanning conducted from 2008 to 2014 and has a horizontal and vertical accuracy of ±40 and ±15 cm, respectively. The 10 m × 10 m digital elevation map was upscaled to 100 m × 100 m and the mean slope was used to determine the final slope of a pixel. Depending on the resulting slope, the pixel was categorized into ground based (slope $\leq$30%) or non-ground based (slope $>$30%) harvesting, as proposed by Kühmaier and Stampfer (2010). Areas with slopes $>$30% are considered to be unsuitable for plenter forest management.

2.3.4. *Road network data*

The road network information across Styria, representing the situation in September 2023, was obtained from the Federal Office of Metrology and Surveying (Abteilung Landschaftsinformation, 2023). The data is freely available and uses orthophotographs, airborne laser scanning and auxiliary information. The data set covers all major and minor road types in Styria, including tractor paths and forest roads, with an accuracy of ±3 m. For our analysis, we considered state roads, regional roads, tractor paths and forest roads as relevant for harvesting operations and excluded motorways and highways.

The map of Styria's road network is used to identify the distance of a stand to the next (forest) road. Stands located within 100 m of a road are considered as “economically accessible” and thus suitable for plenter forest management. Fig. 3 summarizes the different working steps and data integration of our analysis starting with the identification of the total forest area, the ecological limitations followed by the technical-economic constraints.

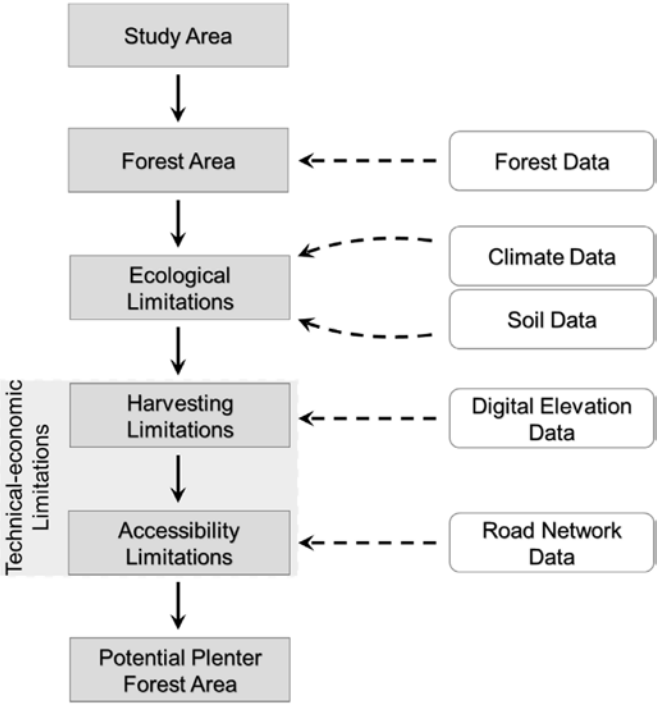

Fig. 3. Conceptual outline and data integration to identify areas suitable for plenter forest management for Styria, Austria. The analyses are performed at 1 ha resolution, the minimum stand size for plenter forest management (Schütz, 2001).

3. Results

3.1. *Ecological limitations*

Under current climate conditions, 42.7% of the forest area in Styria is highly suitable for silver fir mixed with at least one other tree species suitable for plenter forest management (Fig. 4). 44.5% of the forest area is moderately but not highly suited for fir (suitability index between 0.5 and 0.8). The remaining 12.8% are unsuitable for silver fir and thus not suitable for plenter forest management (Fig. 4). We only consider highly suitable areas appropriate for plenter forest management.

3.2. *Harvesting limitations*

Besides ecological limitations, plenter forest management is also limited by cost-efficient harvesting methods such as ground-based extraction systems, which are limited to terrain with slopes $\leq$30%. Applying these limitations to the ecologically highly suitable plenter forest areas (Fig. 4), the potential plenter management area is further reduced by 6.9%–35.8% (see Fig. 5).

3.3. *Road accessibility*

An additional technical-economic limitation is the distance of the plenter forest to the next (forest) road, since the extraction distance of any ground-based harvesting system strongly derives the final harvesting costs. In this study, we assume that the cost-efficient extraction distance has to be $\leq$ 100 m.

Applying the available road network data and assuming timber extraction using tractor or skidder with cable winches, the potential plenter area is further reduced by 7.7%–28.1% (Fig. 6) of the total forest area. Fig. 6 and Table 2 provide an overview of the estimated current plenter forest potential of Styria under current climatic conditions considering (i) the ecological and (ii) the technical-economic limitations expressed by the harvesting conditions (slope $\leq$30%) and the distance to the nearest road ($\leq$100 m).

3.4. *Changes in the potential plenter forest area due to climate change*

Changing climate will influence the ecological limitations for plenter

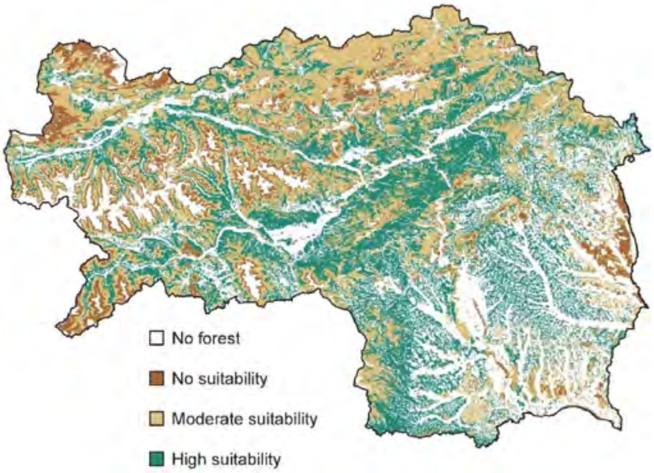

Fig. 4. Spatial distribution of potential plenter forest area in Styria based on the suitability of silver fir mixed with at least one other tree species under the current climate.

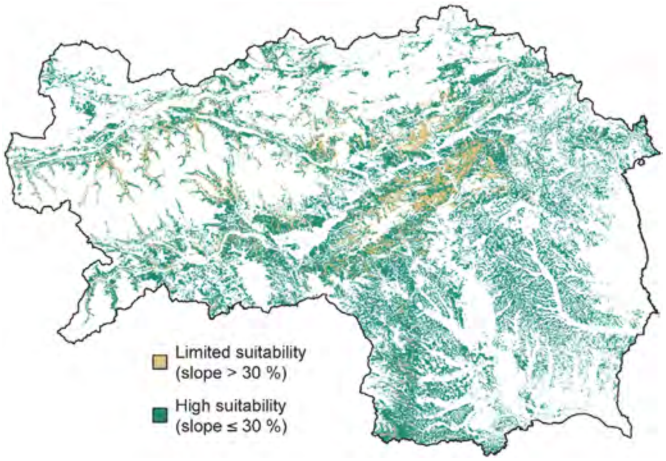

Fig. 5. Spatial distribution of potential plenter forest area in Styria based on the tree species suitability and harvesting conditions under the current climate.

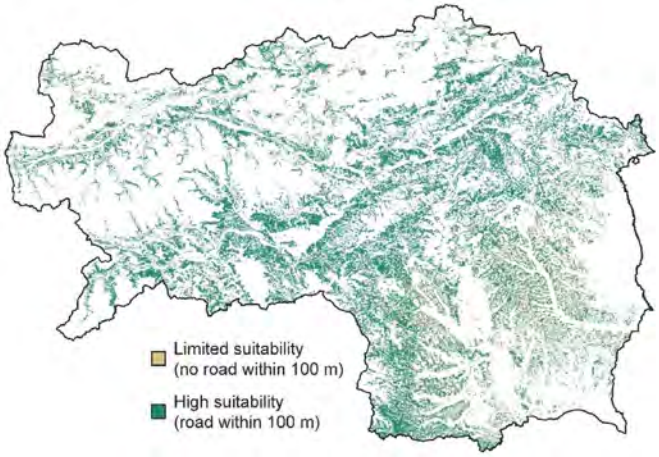

Fig. 6. Spatial distribution of potential plenter forest area in Styria based on the tree species suitability, harvesting conditions and road accessibility under current climate.

Table 2
Overview of the current limiting factors for potential plenter forest management of our case study Styria, Austria, including the proportion of carbonate and siliceous areas.

Step	Limitation	Area (ha)	Area (%)	Change (%)	Carbonate (%)	Siliceous (%)
1	Forest Area	1,086,153	100		17.3	82.7
2	Ecological	463,628	43	−57	0.7	99.3
3	Harvesting	388,790	36	−7	0.5	99.5
4	Accessibility	305,349	28	−8	0.5	99.5

forest management since temperature and precipitation patterns are important drivers for species composition and forest growth. Under the current climatic conditions (i.e. the average conditions of the climate period 1989–2018) and the existing technical-economic constraints, about 28% of the forest area in Styria, Austria, is potentially suited for plenter forest management (Table 2). Forests on siliciclastic bedrock are generally better suited compared to forests growing on carbonate bedrock (Table 2). For assessing future changes in the potential plenter forest area due to changing climate, we obtained the temperature and precipitation date from the RCP 4.5 and the RCP 8.5 scenarios and re-run the expert model (Fig. 1) for the climate period 2071–2100. We only considered potential changes in the ecological limitations. The technical-economic limitations harvesting (slope ≤30%) and accessibility (distance to next road ≤100 m) were assumed to remain constant (see Table 2, Steps 3 and 4).

Table 3 provides the results for the RCP 4.5 and RCP 8.5 by bedrock type (carbonate or siliceous) and by elevation class. Fig. 7 shows the spatial distribution by scenario for the average climate conditions of the period 2071–2100. The results suggest that the potential plenter forest area for the RCP 4.5 may decline by about 6.3% from 305,349 to 286,098 ha and for the RCP 8.5 scenario by 31.7% from 305,349 to 208,421 ha compared to the current potential plenter forest area.

4. Discussion

281% or about 305,000 ha of the forest area in the province of Styria, Austria, is potentially suitable for plenter forest management (Table 2, Fig. 6) according to the current autecological and technical-economic conditions, based on a high suitability of silver fir mixed with at least one other shade tolerant tree species, terrain with a slope ≤30%, as well as a maximum distance to the next road or forest road of ≤100 m. In Central Europe, large-scale clear-cuts followed by replanting activities mainly with Norway spruce has limited the regeneration of silver fir, e.g. in southern Germany (Spiecker et al., 1996), north-western Romania (Feurdean and Willis, 2008) or the Czech Republic (Dobrowolska et al., 2017). In addition, severe browsing impacts have strongly limited silver fir regeneration during the past 50 years. This also applies to our case study area Styria, where clear-cut management and replanting with Norway spruce took place on 70% of the total forest area (BFW, 2022). The historic reasons were the transport of wood by water drifting until the Second World War (Grabner et al., 2004; Reismann, 2022). While it was common to drift silver fir from the German Black Forest to the Netherlands (Schütz et al., 2012), in Styria, silver fir was considered less suitable for water drifting compared to Norway spruce due to its tendency to develop wet-heartwood (Grabner et al., 2004). Furthermore, the Austrian wildlife impact monitoring clearly shows that the browsing pressure from ungulates in large parts of Styria (Schodterer and Kainz, 2022) resulted in a severe decline of silver fir regeneration (Dobrowolska et al., 2017; Gill, 1992). Similar impacts of ungulates on silver fir regeneration have been reported for Slovenia (Ficko et al., 2011; Klopčič et al., 2010) and the reduction of ungulate density are suggested as the best methods to promote silver fir regeneration (Côté et al., 2004; Feurdean and Willis, 2008; Ficko et al., 2018). Due to these historical impacts, silver fir now accounts for only about 6% of the forest area in Styria (BFW, 2022) and this may be considered a major constraint in expanding plenter forest management within the region.

Our results show (Table 2) that ecologically, 43% of the forest area in Styria would be potentially suitable for plenter forest management including silver fir and an additional shade tolerant mixture species. This number is similar to the results of the national forest inventory, suggesting a potential natural vegetation with silver fir of about 50% of the forest area in Styria (BFW, 2022).

Forest managers often consider the knowledge gap regarding the ecological limitations of plenter forests in an area of climate change, as a key limitation affecting the uptake of continuous-cover forestry (Mason et al., 2021). Our study addresses this problem by integrating forest stand transformation with projections of changes in climate conditions for tree growth. The results show that for the period 2071–2100, the ecological suitability according to the (i) RCP 4.5 scenario is expected to decrease from 305,349 ha (Table 3, Baseline) to 286,098 ha (Fig. 7, Table 3, Total RCP 4.5) and for the (ii) RCP 8.5 scenario to 208,421 ha (Fig. 7, Table 3, Total RCP 8.5). Siliceous bedrock sites are better suited for plenter forest management versus carbonate bedrock sites (Table 3), since carbonate bedrock sites exhibit a lower water retention capability (see also Ewald, 2004; Ficko et al., 2011).

In lower elevations, both climate change scenarios suggest a severe reduction in plenter forest area mainly due to unfavourable growing

Table 3
Distribution of the potential plenter forest area in Styria, Austria, categorized by tree species suitability, harvesting limitations (slope ≤30%) and road accessibility (≤100 m), across different climate scenarios and bedrock types. The table also includes the corresponding delta (Δ) values, indicating changes in potential plenter forest area compared to the baseline scenario.

Elevation class	Scenario	Carbonate bedrock		Siliceous bedrock		Total	
		Plenter area	Δ	Plenter area	Δ	Plenter area	Δ
		(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
Low	Baseline	704		66,055		66,759	
	RCP 4.5	74	−630	41,094	−24,961	41,168	−25,591
	RCP 8.5	150	−554	5712	−60,343	5862	−60,897
Middle	Baseline	1530		236,998		238,528	
	RCP 4.5	1227	−303	228,670	−8328	229,897	−8631
	RCP 8.5	1175	−355	181,974	−55,024	183,149	−55,379
High	Baseline	0		62		62	
	RCP 4.5	5	5	15,028	14,966	15,033	14,971
	RCP 8.5	83	83	19,327	19,265	19,410	19,348
Total	Baseline	2234		303,115		305,349	
	RCP 4.5	1306	−928	284,792	−18,323	286,098	−19,251
	RCP 8.5	1408	−826	207,013	−96,102	208,421	−96,928

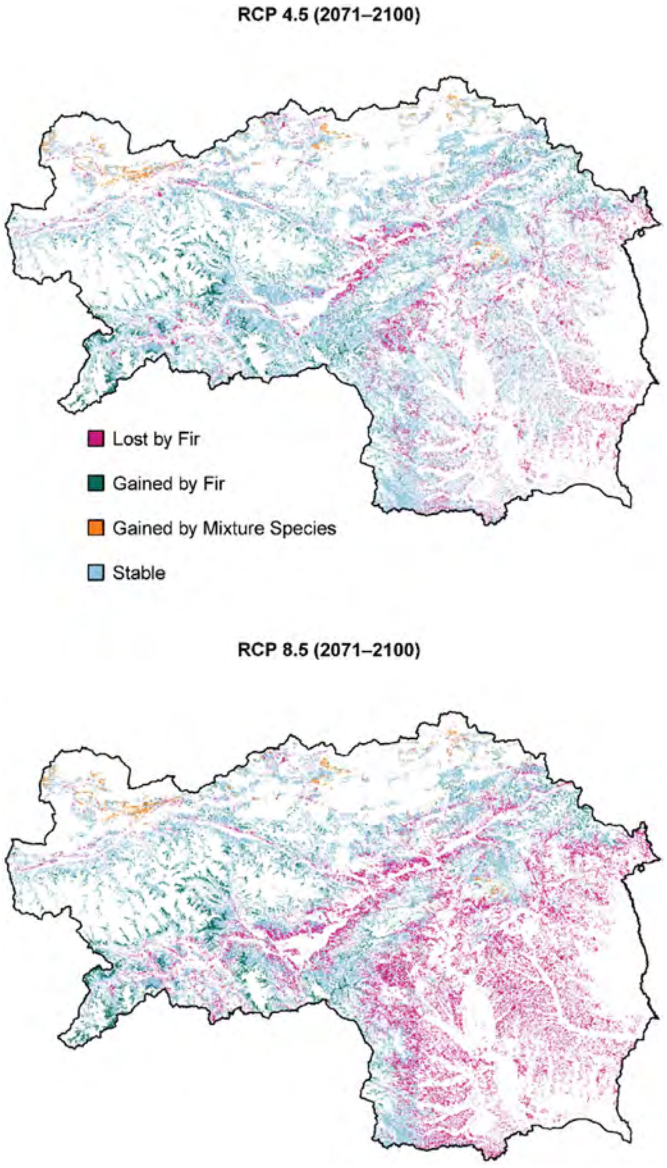

Fig. 7. Projected shifts in potential plenter forest area under RCP 4.5 and RCP 8.5 climate scenarios for the climate period 2071–2100.

conditions for silver fir in warmer and dryer areas, as found in other studies (Feurdean and Willis, 2008; Ficko et al., 2011; Lebourgeois et al., 2010). In the middle elevation areas, a minor loss can be expected on siliceous bedrock for both scenarios, while for high elevation class an increase in plenter forest area is predicted for both scenarios (Table 3). With increasing temperature, silver fir expands in areas with high precipitation and lower mean temperatures (Fig. 7), which is consistent with the findings of Chauchard et al. (2010) and Ficko et al. (2011). The suitability of plenter forest management increases on carbonate sites as with hornbeam and linden, new potential species mixtures may occur (Fig. 7). Note that for these future scenarios we assumed no changes in the technical-economic constraints (slope ≤30%, distance to the next road ≤100 m).

Although this study provides a roadmap for stand transformation integrating climate change effects, it may also have some notable limitations. The current state of the forest in Styria is not considered. Including data on canopy structure could yield information on how much of the forest potentially suitable for plenter forest management is already managed this way. There are also uncertainties regarding the results of the tree species suitability model because of possible errors during field sampling or uncertainties in the modelling process of the input data. Additionally, possible other restrictions that could further reduce the potential plenter forest area are administrative or cultural challenges (Puettmann et al., 2015). Broadening the plenter management from “single tree harvesting” towards “group selection” or “group harvesting”, may also promote more light demanding species and thus enhance the share of uneven-aged management.

5. Conclusion

We found that the potential of plenter forest in Styria diverges strongly from its actual situation. Under the current climatic conditions (average for the period 1971 to 2018) 281% or 305,349 ha of the forests in Styria are potentially suitable plenter forest management. Projecting the plenter forest suitability to the period 2071 to 2100, using the data of the climate change scenario RCP 4.5 and RCP 8.5, the potential area is estimated to decline to 286,098 and 208,421, respectively. This shows that not just even-aged forests, but also plenter forests are susceptible to climate change. The main reasons for these negative changes are the unfavourable growing conditions for silver fir in the lowlands under climate change.

From a forest management perspective, the reintroduction of silver fir on sites where it is currently absent, is a first step towards increasing the share of plenter forests. This will require a reduction of the browsing pressure, an extension of the network system where necessary, and providing training for forest managers in plenter forest management.

CRediT authorship contribution statement

Mathias Leiter: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christoph Pucher:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Kessler:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Ferdinand Hönigsberger:** Writing – original draft, Conceptualization. **Manfred J. Lexer:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Harald Vacik:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Hubert Hasenauer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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