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Regeneration of the Austrian forests and browsing impact – Insights from the latest National Forest Inventory

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Abstract

The initial development stage of forests forms the basis for the future tree generation. Various driving and interacting factors determine the regeneration process at small and large scale. Based on the latest Austrian National Forest Inventory 2016–2021 the regeneration assessments and estimation methods were collated. Analyses were conducted to estimate the forest area regarding regeneration necessity and occurrence, the causes of regeneration deficits, the origin from natural and artificial regeneration, tree species occurrence as well as browsing impact.

The results show a sea level gradient of increasing shares of necessary but missing regeneration, ranging between 15% at the lowest and 60% at the highest altitudes. Accordingly, high shares can be found in protective forest without yield (50%) and in the growth regions of the mountainous areas of the Alps (up to 40%). Due to the multitude of driving and interacting factors, the assessed causes of regeneration deficits show divers patterns. Light as a limiting factor appears to be more relevant at low altitudes, and competition through ground vegetation is highest at low and high altitudes. The influence of the humus layer on the seed bed was assessed to increase with altitude, as well as the impact of forest pasture, while game browsing as cause of regeneration deficits show no clear tendency over the analysed strata. About 91% of the necessary and occurring regeneration originates from natural regeneration and the remaining from artificial or a mixture of both regeneration types. The number of tree species in the ground vegetation layer decreases with altitude. Considering browsing impact the results show percentages of affected areas between 40% and 80%. The highest browsing impacts were found at intermediate altitudes between 600 and 1,500 m above sea level.

From a large-scale perspective as provided by NFIs, the results show divers patterns of regeneration necessity and occurrence and impacts on the regeneration. Representative large-scale monitoring by NFIs provides the opportunity to identify and quantify the adverse impacts and forest strata that are affected by regeneration deficits, and therefore support the development of forest management strategies that aim at the establishment of the future tree generation under changing climate conditions.

Keywords: climate change; natural regeneration; regeneration deficits; sample plot; tree species composition; ungulates

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1. Introduction

The initial development stage of forests forms the basis for the species and structural composition of future forests and their potential regarding wood productivity, carbon sequestration, biodiversity, conservation, and protective functions. Shaping a future climate-adapted tree generation in the forests has become a major topic (e.g., Muller et al. 2019; Brandl et al. 2020; Fuchs et al. 2022) and underlines the crucial importance of the regeneration phase under changing environmental conditions. Changes in tree species composition and distribution (Dyderski et al. 2018; Boisvert-Marsh et al. 2019; Scherrer et al. 2022), the occurrence of natural disturbances (Kramer et al. 2014; Hlásny et al. 2022), and acceleration of forest ecosystem dynamics (Pretzsch et al. 2014; Thom et al. 2022) impact the regeneration process and related forest management considerations. In view of rising temperatures and longer drought periods the regeneration of certain drought-adapted or deep-rooting tree species like e.g., silver fir (*Abies alba* Mill.) and oak (*Quercus* sp.) becomes more and more relevant to establish resilient future forest ecosystems.

The regeneration process is determined by a multitude of driving and interacting factors that render forest regeneration a stochastic process (Käber et al.

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2021). Along the trajectory from tree flowering and seed generation and dispersal until the establishment of the young trees many abiotic and biotic factors and anthropogenic influences affect the development of the regeneration at small and large-scale. Influencing factors include stand and site conditions that impact competition, mortality, growth, temperature, precipitation, light availability, seed bed, seed predation by small mammals, and game impact (e.g., Madsen 1995; Munier et al. 2010; Frei et al. 2018; Nopp-Mayr et al. 2023). Browsing has been repeatedly shown to have a considerable influence on the regeneration (e.g., Kupferschmid et al. 2019; Fuchs et al. 2021; Angst & Kupferschmid 2023), in particular on plants that survived the previous adverse impact factors. In recent decades the population of wild ungulates has increased in Europe (Carpio et al. 2021). In Central Europe the hunting bags have tripled during the last 40 years (Reimoser & Reimoser 2016). Natural disturbance areas with subsequent regeneration and young stands preferred for shelter by roe deer (*Capreolus capreolus* L.) and red deer (*Cervus elaphus* L.) are expected to contribute to further increases (Reimoser & Gossow 1996; Hlásny et al. 2021).

Forests are either regenerated artificially by planting or sowing, or naturally by utilizing the already existing seedlings and saplings for establishing a new stand. According to Forest Europe (2020) about 66% of the European forests originate from natural regeneration, 29% from planting or seeding, and 5% are coppice forests. The shares of natural and artificial regeneration differ between European regions, accounting for 61% and 35% of the forest area in Central-West Europe and 48% and 44% in Central-East Europe. However, artificial regeneration by planting has been decreasing during the last years in Austria and is limited by the tree seed supply and plant availability from forest nurseries (Schüler et al. 2023), a constraint that has been recognized also globally (Jalonen et al. 2018). Nevertheless, under changing climate conditions regeneration by planting or sowing provides the opportunity to shape the regeneration regarding tree species composition and genetic composition. Natural regeneration originates from the previous stand and its genetic constitution, raising the question of climate-adaption of naturally regenerated trees (Williams & Dumroese 2013; Gömöry et al. 2020).

National Forest Inventories (NFIs) conduct statistically representative assessments in regular time intervals and provide reliable information about the state and change of forest ecosystems (Tomppo et al. 2010; Vidal et al. 2016a). Various tree-, stand- and site-specific variables are recorded during the field measurements and in many cases include the regeneration stage (e.g., Gabler & Schadauer 2008; Vidal et al. 2016a; Fischer & Traub 2019; Breidenbach et al. 2020; Gasparini et al. 2022). Over the recent decades the assessments by NFIs have thematically broadened and lately many NFIs have included additional assessments of trees below the minimum threshold of the diameter at breast height (dbh) measurement (Gschwantner et al. 2022). The regeneration assessments can be expected to differ among European NFIs (McRoberts et al. 2010; Alberdi et al. 2016).

About half of the Austrian territory is covered by forest and regularly monitored by the Austrian NFI (Gschwantner et al. 2010). Regeneration assessments are an important part in the NFI field campaigns (Gabler & Schadauer 2008; Gschwantner et al. 2016a; Hauk et al. 2016) and cover several of the previously mentioned aspects. Basic information about forest regeneration is published and part of the standard results of the Austrian NFI (BFW 2022). Since the NFI allows for regeneration and game impact results at country- and federal state-level but not for political districts, a second monitoring system, the Austrian Game-Impact-monitoring (WEM) had been developed aiming at the evaluation of game impacts and the generation of information for prevention measures (Schodterer 2012). It is based on specific grid sizes for each district with a target minimum number of 40 sample plots having a size of 100 m^2. The assessment methods are largely similar to the NFI and provide comparable results on national and federal state level. However, the WEM results can be given in percentages and not per hectare of forest area. In this study we focus on the data provided by the Austrian NFI.

The main objectives of this study are to 1) review and collate the assessments, estimation methods and information from the latest Austrian NFI 2016–2021 about forest regeneration, and to conduct additional analyses about the 2) current status of regeneration necessity and occurrence, 3) the causes of regeneration deficits, and 4) the features of necessary and occurring regeneration regarding origin, tree species occurrence and game impact. The analyses were performed for the geographical strata altitude and growth regions, and for forest management categories.

2. Material and methods

2.1. Study area

Austria has a country area of about 8.39 million ha (Statistik Austria 2022). About 4.02 million ha are covered by forests and thus represent 47.9% of the territory. The forest area is distributed over an elevational range from 120 m at the lowest to 2,200 m at the highest altitudes and covers a broad gradient of bio-geo-climatic conditions from the Pannonian and Subillyrian East to the Central Alps in the West, from the Alpine fringe in the South to the Bohemian massif in the North (Fig. 1; Kilian et al. 1994).

In the Austrian forests the main tree species in terms of their share of tree-covered forest area are Norway spruce (*Picea abies* [L.] H. Karst., 56%), European beech

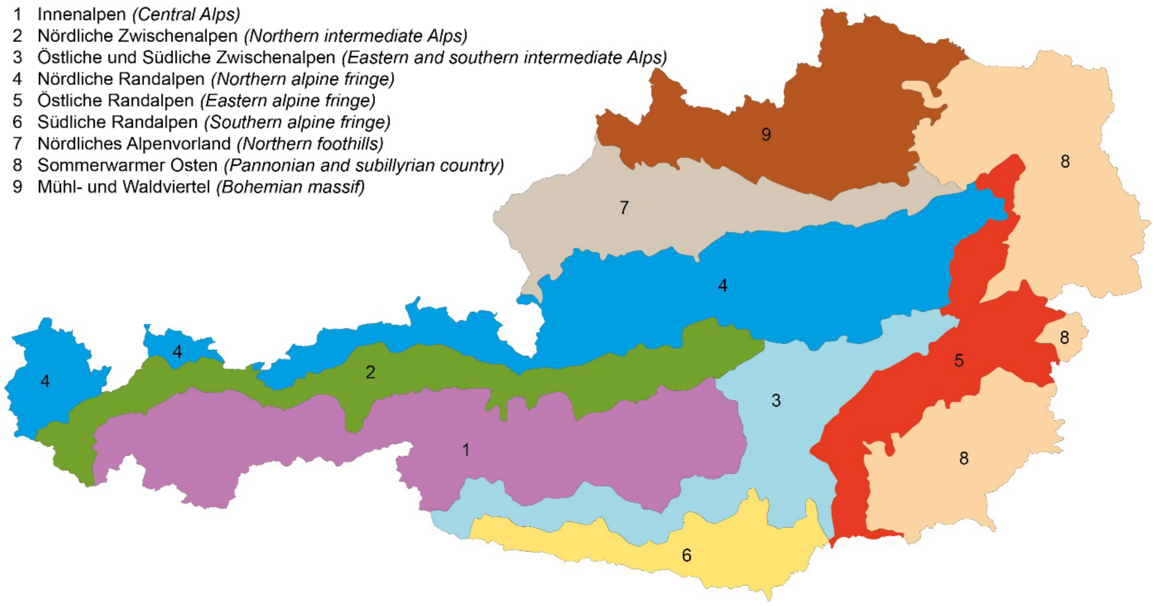

Fig. 1. Growth regions of Austria (Kilian et al. 1994).

(*Fagus sylvatica* L., 13%), European larch (*Larix decidua* Mill., 6%), Scots pine (*Pinus sylvestris* L., 5%), Silver fir (*Abies alba* Mill., 3%) and Oak species (*Quercus* sp., 2%). The other conifer and broadleaved species occupy 2% and 14% of the tree-covered forest area (BFW 2022). Productive forest has an area of 3.36 million ha, 0.49 million ha belong to protective forest without yield and 0.16 million ha are permanently unstocked due to forest management (e.g., forest roads, timber yards) or natural reasons. Productive forest can be further distinguished into the management categories of production forest (88%), coppice (2%) and protective forest with yield (10%). Protective forest without yield includes accessible (55%) and inaccessible forest terrain (45%).

2.2. The Austrian National Forest Inventory

General description

The Austrian NFI conducts at regular time intervals assessments on a systematic sampling grid covering the whole Austrian territory (Gabler & Schadauer 2008; Gschwantner et al. 2010, 2016a). The latest NFI cycle covers the time period 2016–2021. The sample plots are arranged in square-shaped clusters with a side-length of 200 m and permanently established at the intersections of the sampling grid. The sample plots are located at the corners of the clusters. The total sample consists of 22,300 plots and about 11,000 plots are situated on forest land. The sample plots consist of a small circular plot of 21.2 m^2, an angle count sample (Bitterlich 1948) with a basal area factor of 4, and a large circular plot of 300 m^2. The latter is the basis for the assessment and attribution of stand- and site-specific variables that include among others forest management type, stand layers, growth classes, age classes, growth regions, and sea level, as well as the regeneration assessments. Forest plots that are covered by different landuse categories (e.g., forest, non-forest) or stand types (e.g., tree species, age-classes, growth classes, management types) are subdivided into sub-plots and assessed separately. The sub-plot size is given in 1/10-shares of the 300 m^2 plot (Gabler & Schadauer 2008; Gschwantner et al. 2010).

Regeneration assessments

On the sample plots specific regeneration assessments are implemented that cover the accessible forest area, thus including productive forest and the accessible terrain of protective forests without yield. However, coppice forests, shrub land dominated by dwarf mountain pine (*Pinus mugo* Turra) or green alder (*Alnus viridis* [Chaix] DC.), and permanently unstocked parts of the forest like forest roads and timber yards are outside the scope of regeneration assessments. Various criteria are applied in the regeneration assessments which were elaborated and defined by expert survey (Schodterer 1999, 2001) and are specified in detail in the field instructions of the Austrian NFI (Hauk et al. 2016). The regeneration assessments refer to the height class from 10 to 130 cm, thus seedlings below 10 cm are not considered in the assessments. The regeneration assessments basically include the distinction in regeneration necessity and regeneration occurrence. Both regeneration necessity and occurrence are binary variables and yield a 2 × 2 matrix of regeneration necessary/occurring, necessary/not occurring, not necessary/occurring, and not necessary/not occurring. The occurrence of regeneration is coded 1 if the required minimum number or more tree seedlings and saplings are present on the plot and coded 0 otherwise. The minimum number depends on the regeneration height (Table 1). The assessment of occurrence considers first the highest saplings and proceeds with the next lower height classes. Regeneration necessity is coded 1 in the cases of harvested areas, young-growth and afforestation areas, towards the end of the stand development in the last fifth of the rotation length, and to maintain a continuous stocking in protective forests and Plenterwald. The regeneration assessments differ depending on the necessity and occurrence and are summarized in Table 2.

Table 1. Minimum tree numbers of seedlings and saplings for regeneration occurrence on a 300 m^2 sample plot (Hauk et al. 2016).

Height (cm)	Minimum tree number
10	150
20	50
30	30
40	25
50	21
60	19
70	17
80	15
90	14
100	13
110	12
120	11
130	10

Table 2. Overview on regeneration assessments by the Austrian National Forest Inventory (Hauk et al. 2016).

Forest area		Occurrence	
		yes	no
Necessity	yes	• Origin natural or artificial • Area of regeneration patch • Adverse impacts on regeneration • Number classes by height classes • Species of natural forest vegetation • Browsing percentage • Regeneration on dead wood • Share of dead trees • Number of dominant plants • Number of remaining plants • Features of dominant plants	• Reasons for assessing "no occurrence" • Regeneration obstacles
	no	• Number classes by height classes • Species of natural forest vegetation • Browsing percentage	—

For the purpose of this study, the analyses focused on the forest area classified by regeneration necessity and regeneration occurrence, the causes of regeneration deficits, the origin of regeneration, tree species occurrence and the browsing impact. If the plant number is below the required minimum number for necessary regeneration occurrence, the situation is further evaluated and no occurrence is distinguished into three classes, indicating whether no plants, only seedlings below 10 cm, or an insufficient number of plants is present. Furthermore, the reasons limiting regeneration establishment are assessed (e.g., light deficits, ground vegetation, humic layer, forest pasture, game browsing).

Other assessments related to regeneration

In addition to the specific regeneration assessments several other variables are recorded on the sample plots that relate to regeneration such as canopy closure, species occurrence, natural forest vegetation, soil conditions or deadwood occurrence (Section 2.2. General description). The canopy closure describes the ground coverage by tree crowns and thus the light conditions in a stand. The canopy closure is visually assessed and guided by the following classes (Hauk et al. 2016):

- Open: Space between tree crowns large enough for an additional crown of average size. Includes the stand structures at the alpine tree line with open areas and tree groups.
- Light: Space between tree crowns too small for an additional crown of average size.
- Closed: No space between tree crowns but tree crowns do not merge.
- Dense: No space between tree crowns, tree crowns merge and some crowns diminish.

Regeneration below the canopy is not considered and open-growing regeneration is considered in the canopy closure assessment. The species occurrence is assessed by four stand layers, i.e. an upper and a lower tree layer, a shrub layer and a ground vegetation layer. The latter has been taken into consideration in the present study. Species occurrence distinguishes between single, rare and ground coverage classes of 5%-width. The natural forest vegetation describes the species community that establishes under the local climate and soil conditions in absence of anthropogenic influences. The identification key is available from Hauk et al. (2016) and mainly based on the forest community classification by Mayer (1974).

2.3. Browsing assessments

On the sample plots located in stands with necessary and occurring regeneration, the impact of game due to browsing and fraying is evaluated on the one hand by assessing the browsing impact per tree species and height class in terms of shares of plants with browsing of the main shoot during the last year:

- no browsing of main shoots
- 1–50% browsing of main shoots
- 51–90% browsing of main shoots
- > 90% browsing of main shoots.

On the other hand, further particular assessments are made on dominant plant individuals within the regeneration. These plants can be considered as most relevant for the future development of the stand regeneration. Their number is assessed by tree species and four height classes. Within this class of dominant plants five individuals are systematically sampled by selecting the five trees of a tree species tallest and closest to the plot centre. On each of these plants the browsing of the lateral shoots and main shoot over the last five years and the fraying of the stem are assessed. Based on these assessments the assessed plants were classified as:

- browsing of lateral shoots less than 90% – no game impact
- browsing of more than 90% of lateral shoots or single browsing of main shoot – game impact
- multiple browsing of main shoot or fraying – game impact.

For the assessment of the plot regarding game impact a comparison of target and actual regeneration is made. When a sufficient number of plants without game impact of target and admixed tree species of the natural forest vegetation is present (positive target – actual comparison), the plot is classified as "without game impact". When a sufficient number of plants is present, but not a sufficient number without browsing impact, then the plot is classified as "game impact because of target – actual comparison". When the number of dominant plants is not sufficient for a target – actual comparison, then browsing percentages are used for assessing the game impact. If these percentages exceed the critical thresholds, then the plot is classified as "game impact because of browsing percentage" and otherwise as "without game impact".

2.4. Data analyses

Forest inventory estimates typically are mean values and totals for a specified forest stratum and associated sampling errors describing the statistical uncertainty (Braun 1969). The assessments of regeneration relate to the forest area and the respective estimation procedures based on the sample plot data of the 300 m² plots from the NFI and the area of the Austrian territory according to Statistik Austria (2022). Since sample plots are subdivided according to land-use categories and stand types (Section 2.2. General description) the number of 1/10-shares is used in the ratio estimator that multiplies the area of the Austrian territory with the proportion of total number 1/10-shares of the sample covered by forest (Gabler & Schadauer 2008):

$$W = G \cdot \frac{w}{g} \quad [1]$$

where W is the forest area, G is the total area, w is the number of 1/10-shares covered by forest, and g is the number of total possible 1/10-shares. The ratio of w and g is also denoted as forest cover percent p and can be further detailed as:

$$p = \frac{w}{g} = \frac{\sum_{j=1}^{m} w_j}{\sum_{j=1}^{m} g_j} \quad [2]$$

w_j describes the number of 1/10-shares of cluster j covered by forest, and g_j the total possible number of 1/10-shares of cluster j, and m is the number of clusters within G.

The associated standard error of p is obtained from

$$s.\,e.\,(p) = \frac{1}{g} \cdot \sqrt[2]{\frac{m}{m-1} \cdot \sum_{j=1}^{m} (w_j - p \cdot g_j)^2} \quad [3]$$

and the standard error of W abbreviated as $s.\,e.(W)$ is the multiplication of $s.\,e.\,(p)$ by the total area G:

$$s.\,e.\,(W) = s.\,e.\,(p) \cdot G \quad [4]$$

The formulas can be also applied to calculate results of forest area for various forest strata such as growth regions, forest management types, altitude classes, and further stand or site characteristics. Based on the formula scheme several analyses were conducted and include the forest area subject to regeneration assessments, the area of regeneration necessity and occurrence, causes of regeneration deficits, the origin of necessary and occurring regeneration, and browsing impact. The browsing impact is evaluated in three different ways, as a cause of regeneration deficits, based on a comparison of target and actual regeneration, and browsing percentages.

3. Results

3.1. Regeneration necessity and occurrence

According to the NFI criteria 3,450,000 ha of forest land are within the scope of assessing the necessity and occurrence of regeneration out of the total 4,015,000 ha of Austrian forest area (BFW 2022). Table 3 shows the regeneration assessment area by stand canopy closure classes, indicating the light conditions for ground vegetation in the stands. Open and light stands together have a share of about 25%, closed and dense 60%, and the remaining 15% of the forest area are blanks, shrub area and other forest land outside the scope of regeneration assessments.

Table 3. Forest area within the scope of regeneration assessments by canopy closure classes, other forest land, and total forest area in Austria.

Canopy closure	Forest area (1,000 ha)	Share (%)
Open*	271 ± 11	6.7
Light	723 ± 18	18.0
Closed	1,742 ± 30	43.4
Dense	608 ± 17	15.1
Blanks	86 ± 6	2.1
Shrub area	20 ± 3	0.5
Sum **	3,450 ± 44	85.9
Other forest land ***	565 ± 19	14.1
Total	4,015 ± 46	100.0

Notes: * Contains forest plots located on stand gaps. **Forest area subject to assessment of regeneration necessity and occurrence. ***Coppice forest, shrub land (mountain pine, green alder), inaccessible forest in steep terrain, permanently unstocked parts of the forest (forest roads, timber yards).

Fig. 2 shows the forest area by altitude classes and distinguishes the area within the scope of regeneration necessity and occurrence assessments from other forest land where no regeneration assessments are performed. These areas are more frequent in higher altitudes, and thus also in the central and intermediate alpine growth regions, and in protective forest without yield.

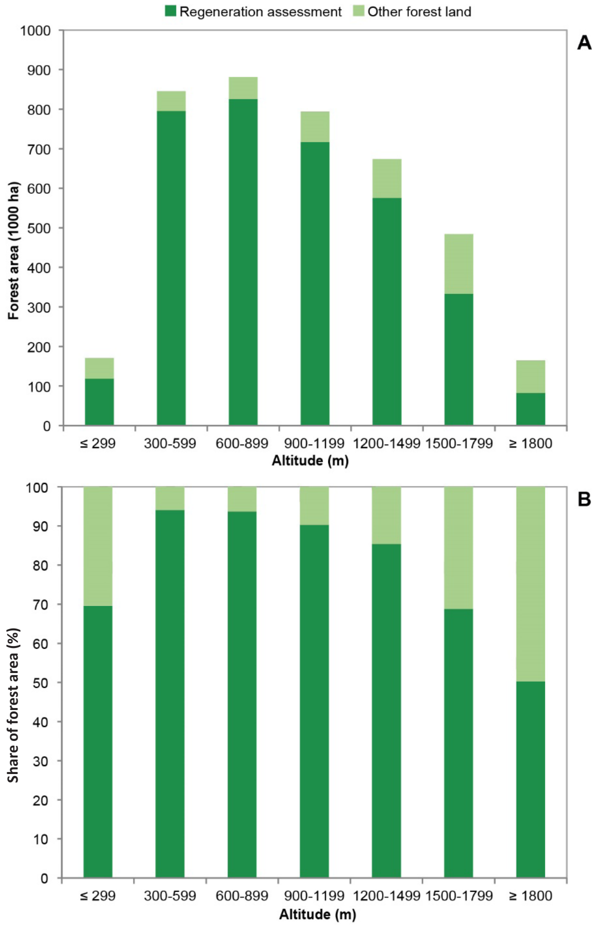

Fig. 2. Area of regeneration assessments by altitude: A) total forest area; B) share of forest area.

Considering the forest area within the scope of regeneration assessments, regeneration occurs on 1,406,000 ha and is similar to the forest area where regeneration is necessary with 1,398,000 ha, corresponding to 41% and 40% of the forest area, respectively (Table 4). On 800,000 ha regeneration is necessary but not occurring in a sufficient amount, this area represents 23% of the assessed forest. About the same area of 808,000 ha features regeneration occurrence although according to the stand development stage regeneration is not necessary. The forest area where regeneration is necessary and also occurring amounts to 598,000 ha representing 17% of the forest area. The forest area with regeneration occurrence is found to about 32% in open and light, 53% in closed, 14% in dense conditions, and 1% on blanks.

"No occurrence" does not mean that regeneration is completely missing, but rather that the number of young

Table 4. Forest area classified by necessity and occurrence of regeneration.

Forest area (1,000 ha)		Occurrence yes	Occurrence no	Sum
Necessity	yes	598 ± 16 (17.3%)	800 ± 21 (23.2%)	1,398 ± 27 (40.5%)
	no	808 ± 20 (23.4%)	1,244 ± 25 (36.1%)	2,052 ± 32 (59.5%)
Sum		1,406 ± 27 (40.7%)	2,044 ± 33 (59.3%)	3,450 ± 44 (100.0%)

plants does not exceed the defined threshold value (Section 2.2. Regeneration assessments). On about 85% of the forest area of necessary and not occurring regeneration seedlings and young plants are present, but not enough to fulfil the criterion of sufficient regeneration occurrence. On 5% of the area only seedlings and plants below 10 cm can be found. On about 10% of the area

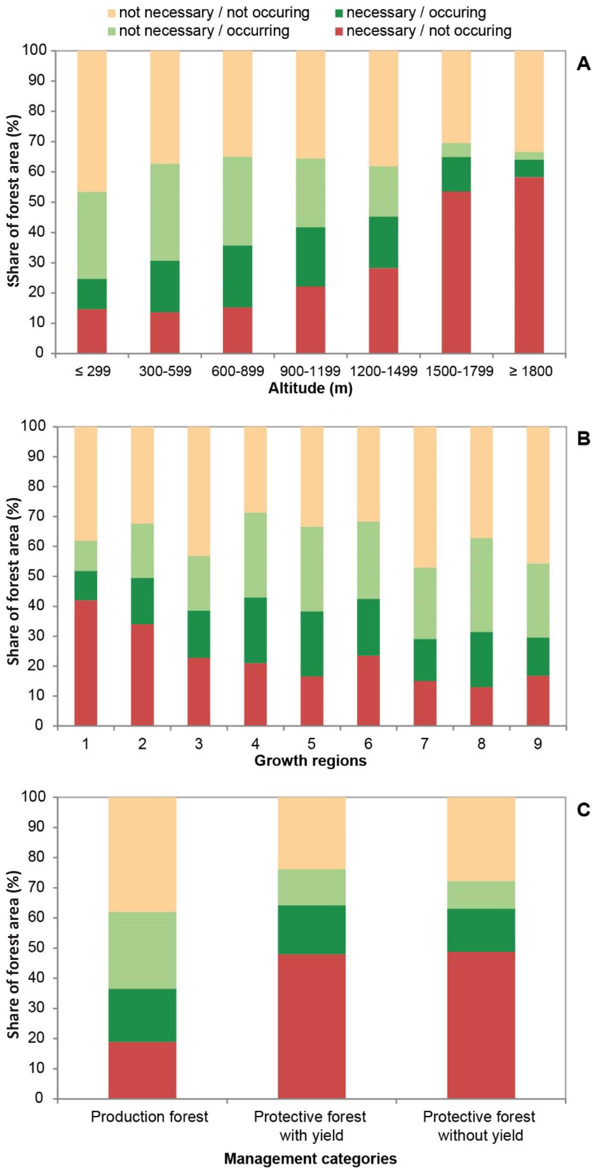

Fig. 3. Regeneration necessity and occurrence in shares of forest area within the scope of regeneration assessment: by A) altitude; B) growth regions; and C) forest management categories.

requiring regeneration the seedlings and young plants are completely missing.

The four classes of regeneration necessity x occurrence and their shares showed differences over altitude, growth regions, and management classes. The area share of necessary regeneration increases with altitude. This effect can also be noticed in the growth regions and forest management categories showing highest necessity in protective forests and growth regions with higher altitudes. Similarly, also the area of necessary and not occurring regeneration increases with sea level, ranging from about 15% in the lowest to almost 60 % in the highest altitudes. Conversely, the area percentage of not necessary regeneration occurrence is highest at low altitudes and decreases towards the higher sea levels. Considering the growth regions, relatively high area percentages of 50% necessary regeneration can be found in the Central Alps and Northern intermediate Alps, whereas the lowest percentages occur in the northern and eastern parts of the country. The percentage of necessary and not occurring regeneration is similarly distributed with highest shares in the central alpine areas and lowest in Northern foothills, Bohemian massif and the eastern parts. Particularly large differences can be noticed between protective and production forest, where the share of necessary but not occurring regeneration is twice as high in protective forest compared to production forest.

3.2. Causes of regeneration deficits

The absence of regeneration can be due to various reasons, e.g., light deficiency, competition by grasses, herbs and shrubs, forest pasture, browsing, erosion and other causes. Overall, on about 154,000 ha or 20% of these 800,000 ha of forest, browsing by ungulates has been assessed as reason for the absence of regeneration, which can be assumed to underestimate the actual game impact since the browsing of small seedlings does not leave assessable traces. On 10% of the area browsing due to forest pasture has been assessed as reason for regeneration deficits. The humic layer, competition by grasses, herbs and shrubs, as well as light deficits are among the reasons for regeneration deficits on 25%, 50% and 40% of the forest area respectively. Tables 5, 6 and 7 show the assessed causes of regeneration deficits for the area of necessary and not occurring regeneration. These causes of regeneration deficits change along the altitude gradient. Light deficits decrease with the sea level, the impact of ground vegetation decreases towards intermediate altitudes and then increases towards the highest altitudes, the influence of the humic layer increases with the sea level, and the influence of forest pasture increases in higher altitudes. Game browsing shows no particular trend but indicates larger impacts in certain strata.

Table 5. Causes of regeneration deficits by altitude on forest areas with necessary but not occurring regeneration.

Causes of regeneration deficits	Altitude (m)						
	< 299	300–599	600–899	900–1,199	1,200–1,499	1,500–1,799	≥ 1,800
	Percentage of area (%)						
Light deficiency	44	53	49	46	39	21	14
Ground vegetation	70	40	40	38	45	67	68
Humic layer	3	15	23	25	27	31	40
Forest pasture	2	1	2	5	9	20	26
Game browsing	24	15	19	20	21	19	20
Other obstacles	28	24	35	37	42	36	42

Table 6. Causes of regeneration deficits by growth regions on forest areas with necessary but not occurring regeneration.

Causes of regeneration deficits	Growth region								
	1	2	3	4	5	6	7	8	9
	Percentage of area (%)								
Light deficiency	27	30	38	42	46	48	43	61	41
Ground vegetation	55	66	55	37	43	36	50	47	45
Humic layer	30	28	26	26	23	23	6	11	25
Forest pasture	19	12	10	7	4	5	0	1	1
Game browsing	18	18	19	27	13	16	15	24	12
Other obstacles	39	30	30	46	28	40	23	23	33

Table 7. Causes of regeneration deficits by forest management categories on forest areas with necessary but not occurring regeneration.

Causes of regeneration deficits	Management category		
	Production forest	Protective forest with yield	Protective forest without yield
	Percentage of area (%)		
Light deficiency	45	28	11
Ground vegetation	46	52	64
Humic layer	21	35	38
Forest pasture	8	15	10
Game browsing	17	23	24
Other obstacles	27	48	70

3.3. Features of necessary and occurring regeneration

Natural and artificial regeneration

Considering the regeneration origin, a large proportion of about 91% stems from natural regeneration (Table 8). Artificial regeneration can be found on about 9% of the forest area featuring regeneration necessity and occurrence. Artificial regeneration occurs frequently in combination with natural regeneration, e.g. with early successional species like birch, poplar, or willow that will not reach the final stand development stage.

Table 8. Natural and artificial regeneration.

Regeneration type	Area (1,000 ha)	Percent (%)
Natural	542 ± 16	90.6
Artificial	13 ± 2	2.2
Natural + Artificial	43 ± 4	7.2
Total	598 ± 16	100.0

Tree species occurrence

The trees species in the regeneration form part of the ground vegetation layer together with other vegetation elements such as shrubs, grasses, ferns, herbaceous plant species and mosses. Table 9 shows the tree species occurrence in the altitude classes for the forest area of necessary and occurring regeneration. The number of tree species in the ground vegetation layer is low under the conditions at high altitudes where only Norway spruce (*Picea abies* [L.] H. Karst.), European larch (*Larix decidua* Mill.), stone pine (*Pinus cembra* L.) and mountain ash (*Sorbus aucuparia* L.) can be found. Towards lower altitudes the number of tree species gradually increases and shows the highest species occurrence between 300 m and 900 m above sea level. Slightly less forest tree species occur in the ground vegetation layer at low sea levels due to the absence of European larch (*Larix decidua* Mill.), black alder (*Alnus glutinosa* [L.] Gaertn.) and goat willow (*Salix caprea* L.).

Browsing impact on regeneration

On average the share of areas with game impact amounts to about two thirds of the forest area with necessary and occurring regeneration. The results show differences between altitude, growth regions and management categories. Game impact appears to be highest in the intermediate altitudes from 600–1,500 m, in certain growth regions and in protective forest without yield (Fig. 4).

Table 9. Occurrence of tree species (×) in the ground vegetation layer by altitude. Single occurrences are excluded from the analysis, sparse included.

Tree species	Altitude (m)						
	< 299	300–599	600–899	900–1,199	1,200–1,499	1,500–1,799	≥ 1,800
Picea abies	×	×	×	×	×	×	×
Abies alba	×	×	×	×	×	×	
Larix decidua		×	×	×	×	×	×
Pinus sylvestris	×	×	×	×	×	×	
Pinus nigra	×	×	×				
Pinus cembra						×	×
Other conifers	×	×	×	×	×	×	
Fagus sylvatica	×	×	×	×	×	×	
Quercus robur	×	×	×	×			
Quercus petraea	×	×	×	×			
Quercus cerris	×	×	×				
Carpinus betulus	×	×	×				
Fraxinus excelsior	×	×	×	×	×		
Acer pseudoplatanus	×	×	×	×	×	×	
Acer platanoides	×	×	×	×			
Acer campestre	×	×	×				
Ulmus glabra	×	×	×	×			
Ulmus carpinifolia	×	×	×				
Castanea sativa	×	×	×				
Robinia pseudoacacia	×	×					
Prunus avium	×	×	×	×	×		
Sorbus aucuparia	×	×	×	×	×	×	×
Betula pendula	×	×	×	×	×	×	
Alnus glutinosa		×	×	×			
Alnus incana	×	×	×	×	×	×	
Tilia platiphyllos	×	×	×	×			
Tilia cordata	×	×	×	×			
Populus tremula	×	×	×	×	×	×	
Salix caprea		×	×	×	×	×	
Other broadleaves	×	×	×	×	×	×	×
Shrub species	×	×	×	×	×	×	×
Mosses	×	×	×	×	×	×	×
Ferns	×	×	×	×	×	×	×
Grasses	×	×	×	×	×	×	×
Herbaceous plants	×	×	×	×	×	×	×

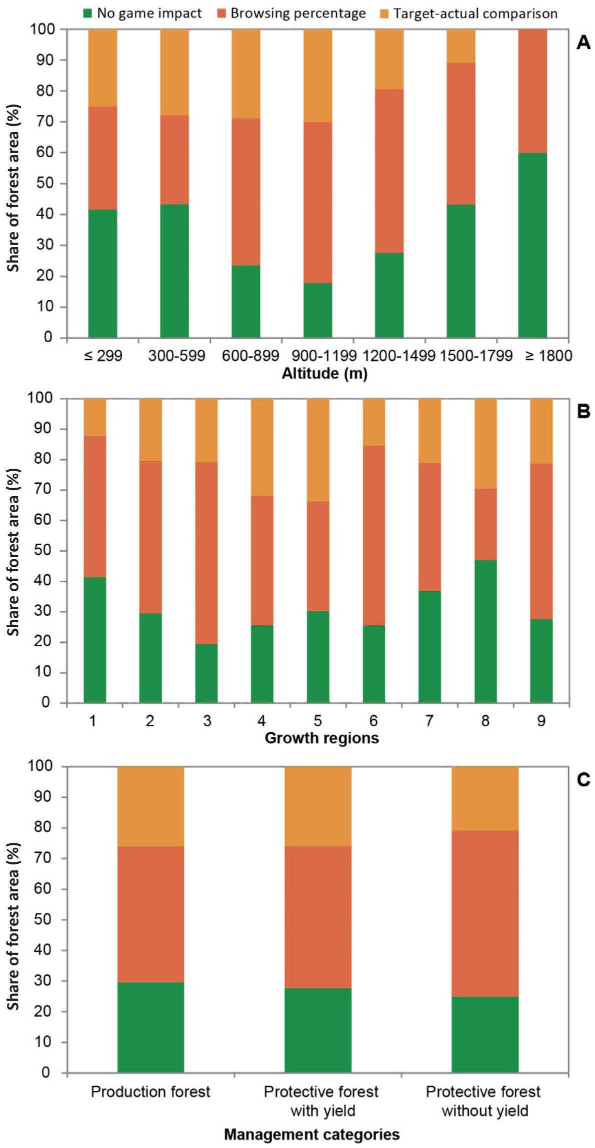

Fig. 4. Game impact in forests with necessary and occurring regeneration: by A) altitude; B) growth regions; and C) forest management categories.

4. Discussion

4.1 Patterns of regeneration necessity and occurrence

The assessments of regeneration necessity and occurrence by the Austrian NFI refer to about 86% of the total forest area, excluding inaccessible forests in steep terrain, coppice forests, shrub areas of mountain pine and green alder, and permanently unstocked parts like forest roads and timber yards. The proportion of assessed areas differs by altitude, growth regions and forest management categories and is lowest in high altitudes and in protective forest without yield mainly due to inaccessible forest and shrub areas. Currently the forest area featuring regeneration necessity amounts to 1,398,000 ha and similarly regeneration occurrence amounts to 1,406,000 ha, resulting in an intersection of 598,000 ha of necessary and occurring regeneration or 17% of the forest area. No sufficient regeneration can be found on 800,000 ha or 23% of the forest area, which however does not mean that no regeneration is present at all. Only on about 10% of this area of insufficient regeneration the seedlings and young plants are completely missing. The assessment criteria of regeneration necessity applied by the Austrian NFI include harvested areas, young-growth and afforestation areas as well as forests towards the end of the stand development in the last fifth of the rotation length, and protective forests and Plenterwald with continuous stocking. Thus, the assessment of regeneration necessity assumes an essential contribution of natural regeneration and results in a relatively large area proportion of 40%. The share of forest areas with regeneration necessity increases from 25% at the lowest altitude and up to 65% in the highest. Actual occurrence of regeneration on these forest areas is highest at the lowest altitudes, vice versa leading to a sea level gradient of missing regeneration. 60% of forest areas at the highest altitudes above 1,800 m have regeneration necessity and no regeneration occurrence, 50% in protective forest without yield, and up to 40% in the growth regions of the mountainous areas of the Alps, and thus underline the importance of the topic of regeneration and adverse influences and conditions in these forest categories.

4.2. Regeneration deficits and browsing impact

Insufficient regeneration occurrence can be caused by various interacting factors and therefore shows divers patterns but indicate that light as a limiting factor is more relevant at low altitudes, competition through ground vegetation is highest at low and high altitudes, the influence of the humus layer on the seed bed increases along the altitude, as well as the impact of forest pasture. Game browsing as cause of regeneration deficits ranges between 15% to 25% of the forest area and can be expected to underestimate the actual game impact since the browsing of small seedlings does not leave assessable traces on the plots. The game impact on necessary and occurring regeneration shows percentages in the range of 40% to 80% of areas affected by browsing depending on the respective forest category. High browsing impacts were found in protective forests with and without yield and indicate the regeneration difficulties in this forest management categories. These results correspond to other findings that describe a considerable influence of game browsing on the regeneration (e.g., Kupferschmid et al. 2019; Fuchs et al. 2021; Angst & Kupferschmid 2023), in particular on plants that survived the seedling stage and the previous adverse impact factors. However, the effects of ungulate herbivory are rather complex and contributes to divers results (Nopp-Mayr et al. 2023). The relevance of applied criteria and thresholds on the study results are indicated also in the present study. In recent decades the population of wild ungulates has increased in Europe (Carpio et al. 2021) and also in Austria (Reimoser & Reimoser 2016). The forest area available as game habitat decreased continuously due to human leisure activities and landscape fragmentation (Reimoser 2020a, 2020b). However, it should be noted that the forest area has steadily increased in Austria during the same time. This concentration of increasing ungulate populations on a decreasing area can be expected to have considerable impact on the forest regeneration.

4.3. Future environmental conditions

Under changing climate conditions, the establishment of climate-adapted and resilient future forest ecosystems has become a major issue (Muller et al. 2019) and involves various considerations about forest productivity, carbon sequestration, biodiversity and protective functions. The expectable changes in terms of duration and severity of drought periods increases the future relevance of deep-rooting tree species like silver fir and oak species. Differences between regeneration tree species regarding game impact and climate change susceptibility can influence the future species composition (Zürcher-Gasser et al. 2023). At the same time the forest regeneration process is affected by a multitude of drivers and interacting factors including competition, light availability, humus condition, and game browsing (Käber et al. 2021). The results of height class occurrence of tree species on the sample plots indicate selective browsing of tree species like silver fir, oaks and other broadleaved tree species. These species can remain in the regeneration layer due to recurring browsing or even disappear while other species like spruce and to some extent also beech are less affected and have competitive advantages to form the future stands. However, these future stands can be expected to have an increased susceptibility to storm, drought, and insect calamities (Seidl et al. 2017).

The establishment of mixed species forests as response to the expectable future development of climate and environmental conditions thus requires a tolerable degree of game impact. A large part of regeneration in Austrian forests originates from natural regeneration and shows an increasing trend over the recent decades (Schodterer 2004, 2011). Natural regeneration under crown coverage is more frequent compared to regeneration on clear-felled areas. The relation between free-standing natural regeneration and freestanding artificial plantings indicates the share of natural regeneration used for establishing the new stands and amounts to currently 80%. Since natural regeneration derives from the previous stand and its genetic constitution, the adaptation and adaptability of naturally regenerated trees to changing climate conditions becomes an essential research question (Gömöry et al. 2020).

4.4. Regeneration assessments and harmonisation of European NFIs

The present study investigated the status of regeneration and factors affecting the regeneration occurrence based on data available from the Austrian National Forest Inventory performed during 2016–2021. Many NFIs regularly conduct regeneration assessments on their field plots (Vidal et al. 2016a), however, large-scale representative information on the early development stage of forests is rarely available (e.g., Vayreda et al. 2013; Kupferschmid et al. 2015). Forest Europe (2020) reports the origin of stands and does not explicitly address the situation of the current regeneration. Similar to other NFI parameters (e.g., Bosela et al. 2016; Gschwantner et al. 2016b, 2019; Alberdi et al. 2020) the regeneration assessments by NFIs can be expected to differ among European NFIs (McRoberts et al. 2010; Alberdi et al. 2016), thus suggesting a comparative study to explore the different methodical approaches and available data. Such information would provide an essential basis for improving the comparability and harmonisation of regeneration assessments in Europe. The importance of consistent monitoring for supporting evidence-based policy decisions has been frequently outlined as e.g. in the new Forest Strategy for 2030 (European Commission 2021).

Important issues for developing a common assessment approach are the large number of seedlings and saplings in the initial development stage that impede the assessment of individual plants and introduce approaches of sub-sampling and classification, and the appraisal of stem numbers and shares for the individual classes. The high mortality rate due to a multitude of impact factors (e.g., Madsen 1995; Munier et al. 2010; Frei et al. 2018) render the early development stage a very dynamic phase and thus introduce particular aspects in regeneration assessments. However, several forest inventory textbooks deal with the topic of regeneration assessment and address methodical issues (e.g., Loetsch et al. 1973; Zöhrer 1980; Schreuder et al. 1993). The experiences from individual NFIs provide a model for developing a harmonised monitoring at European level (Vidal et al. 2016b).

5. Conclusions

Regeneration necessity and occurrence show a trend over sea level. Necessary but missing regeneration ranges between 15% at the lowest and 60% at the highest altitudes, 50% in protective forest without yield, and up to 40% in the growth regions of the mountainous areas of the Alps, underlining the importance of the topic of regeneration and adverse influences in these forest categories. Due to the multitude of driving and interacting factors, the causes of regeneration deficits show divers patterns like light deficiency, ground vegetation, browsing. Considering browsing impact on necessary and occurring regeneration the results show percentages of affected areas between 40% and 80% depending on the stratification and indicate a considerable impact of game on the early development stage of forests.

Representative large-scale monitoring by NFIs provides the opportunity to identify and quantify the adverse impacts and forest strata that are particularly affected by regeneration deficits, and therefore support decision makers in developing forest and game management strategies that aim at the establishment of the future tree generation under changing climate conditions. International harmonisation of regeneration assessments by NFIs would enable for objective comparisons of browsing impact on forests among European countries. Harmonised information on regeneration would provide the opportunity of forest and game management considerations at larger scales and across country borders.

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