

Norway spruce (*Picea abies* (L.) H. Karst.) selection forests at Siljansfors in Central Sweden[☆]

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ABSTRACT

Continuous cover forestry (CCF) is a type of forest management which is based on ecological principles and avoids clearfelling as much as possible. A specialised form of CCF is the selection system which relies on inhomogeneous size structures in mixed-species forests and on the harvesting of individual dominant trees. The selection system was originally invented by upland farmers in Central Europe some 500 years ago and is fairly uncommon in Northern Europe. In our research, we studied two more or less mono-species *Picea abies* selection forests at Siljansfors in Central Sweden that have a comparatively low final stem diameter of 50 cm. We involved dynamic demographic equilibrium modelling to identify an ideal size structure as a reference that ensures sustainability. We compared this reference with the observed empirical stem-diameter distributions and found that both stands are indeed advancing towards the structure typical of single-tree selection systems. One stand is particularly close to this ideal, sustainable structure whilst the other requires more goal-orientated management in the future. Our research confirmed that selection forests with largely only one conifer species and a fairly small final diameter are possible at this latitude. We could also show that the dynamic demographic model can be converted to a simpler static model that is easier to apply in forest practice. Since selection stands are rare in Fennoscandia, the two stands studied at Siljansfors have been and will continue to be important research and management demonstration sites in the future.

1. Introduction

The selection system is a very specialised form of continuous cover forestry (CCF) that was originally “invented” by Central European upland farmers in Austria, France, Germany, Slovenia and Switzerland as early as the beginning of the 15th century (Hasel and Schwartz, 2006). In the German speaking countries, this management system is also known as “plenter” system or “Plenterwald” (selection forest). In the context of farmland management, these selection forests were rather small in scale and together with the agricultural part of the farmers’ business formed a kind of agroforestry estate. The fields were usually worked upon during the growing season whilst forest management took place in winter. Often these selection forests were left without human interventions for many years (Schütz, 2001).

Continuous cover forestry (CCF) is a type of forest management

which is based on ecological and biological principles. Definitions of CCF usually include a number of tenets or principles that can greatly vary between countries and organisations involved (Pommerening and Murphy, 2004). The most prominent tenet of CCF is the requirement to abandon the practice of large-scale clearfelling in favour of more environmentally friendly harvesting and natural regeneration methods.

Unlike most other silvicultural systems, the selection system is not primarily a method for achieving natural regeneration, but constitutes a whole programme of long-term treatments of forest stands. If appropriately managed, selection systems ensure the self-sustainability of timber resources and size structure at stand level, which was the main incentive for Central European farmers to develop this system, since their forest properties were rather small. Selection systems offered the opportunity to selectively harvest predominantly large trees in perpetuity without a need to invest in expensive replanting and in the costly

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thinning of many small trees. More than any other form of CCF, selection forests have no distinct forest generations and the structure of these forests has a tendency towards being composed of trees whose crowns do not touch but fill the whole vertical growing space (Schütz, 2001). The most common intervention in selection forests is the felling of few individuals, mostly large trees at fairly short but irregular thinning cycles. The felled trees are replaced by mid-storey trees which in turn are supplemented by regeneration trees in the understorey. The selection system can be thought of as a kind of *process conservation*, where a forest stand is permanently kept in a disturbance and regeneration phase (Pommerening, 2023). Historically, this silvicultural system is likely to have evolved from coppice with standards, an ancient forest management system partially based on the resprouting ability of certain tree species after felling (Schütz, 2001).

National proportions of selection forests are small (3% in Austria, 1% in France and Germany, 13% in Greece, 12% in Slovenia and 8.4% in Switzerland), i.e. selection forests are comparatively rare in Europe (Mayer, 1984; Schütz, 2001). Half of all selection forests surveyed by Schütz (2001) were located above 1400 m asl, i.e. they are an important element of upland forestry. In Fennoscandia, the uptake of the selection system has been much lower than in Central Europe and by 1950 the conclusion was made that this system was largely unsuitable in Sweden on the grounds of the harsh climatic conditions in the country and a common lack of natural regeneration (Lundqvist, 2017). Despite this negative assessment a few research and practical experiments using selection-system techniques were continued in Sweden such as those in the Siljansfors Experimental Forest in the centre of the country, which we have analysed in this study.

As part of the recent CCF debate, selection forests have come to be appreciated once again for their increased ability to withstand natural disturbances (Dvorak and Bachmann, 2001; Hanewinkel et al., 2014), which in the context of climate change is more important than ever. Selection forests also offer great amenity values in recreation, community and peri-urban forests (Arnberger, 2006). In addition, they play an important role in forest management for protecting human settlements and infrastructure from rock fall, landslides and avalanches (Dorren et al., 2005; Brang et al., 2006; Rammer et al., 2015). In addition, many aspects and structures of selection systems are also relevant to or can be observed in other forms of CCF. Hence any study of this silvicultural system is of great general interest (Pommerening, 2023).

The classic species of selection forests include *Picea abies* (L.) H. Karst., *Abies alba* MILL. and *Fagus sylvatica* L. which dominate such forest types in the Vosges, Black Forest, Jura, Alps and Carpathians (Matthews, 1991). Selection systems, however, are also possible with other species such as *Pseudotsuga menziesii* (MIRB.) FRANCO in mixture with *Tsuga* ssp. and *Thuja plicata* (DONN) EX. D. DON. (Schütz and Pommerening, 2013). Other known species combinations include *Larix decidua* MILL. and *Pinus cembra* L. in the elevated continental valleys of the Alps (Schütz, 2001). In Northern Europe including Northern Germany, mono-species selection forests of either *Picea abies* or *Fagus sylvatica* are not uncommon (Petersen and Guericke, 2004; Schütz, 2006; Pommerening, 2023). In Sweden, more or less mono-species *Picea abies* forests have been the preferred choice for experimenting with selection systems (Lundqvist, 2017), not least for the simple reason that *F. sylvatica* reaches its northern natural distribution limit even in Southern Sweden and *A. alba* is not native to the country.

The objectives of this paper include (1) the spatio-temporal analysis of the stem-diameter structure of two *Picea abies* forest stands at Siljansfors in Sweden that were managed using selection-system techniques. As a reference structure, we (2) fitted dynamic demographic equilibrium models Schütz, 2001, 2006; Schütz and Pommerening, 2013) based on growth and mortality data from the two stands. (3) We translated the dynamic model into a simpler static q factor model for ease of use in forest practice. Finally, (4) we quantified the spatio-temporal deviations of the two forest stands from the demographic models and made recommendations for future forest

management. Since selection-forest methods were only applied loosely at Siljansfors, our hypothesis was that the stand structure markedly deviated from that suggested by the demographic models.

2. Materials and methods

2.1. Siljansfors selection forest stands

The Siljansfors Experimental Forest is located southwest of Mora (60° 52' - 60° 55' N, 14° 19' - 14° 25' E) in the Dalarna County of Central Sweden. Stands 9022 and 9082 (Fig. 1) were treated according to selection-system principles involving individual-tree thinnings and target-diameter harvesting. *P. abies* dominated the two stands with a total basal area larger than 70% during the whole monitoring period. Other tree species with low abundances include *Pinus sylvestris* L. and *Betula* ssp. In both stands, the ground vegetation was dominated by *Vaccinium myrtillus* L. and soil moisture was mesic.

Historically, the transformation of stand 9022 to a selection forest started in 1923. Before that time the stand was an uneven-aged mixed-species forest largely untouched by human interventions (Lundqvist et al., 2013). Stand 9022 is situated at an altitude of 400 m asl and has a total area of one hectare. The stand was divided into four plots of 0.25 hectares each and has a site index¹ of 22 m (Lundqvist, 1993). Stand 9022 was subjected to 11 single-tree selection cuttings at irregular intervals between 1923 and 2017. In the earlier cuttings up until 1965, a large proportion of small and medium-sized trees was removed along with the usual harvesting of large trees (target-diameter harvesting). In 1956, 1965 and 1975, small gaps of 15–25 m diameter were cut as part of the transformation thinnings. Since 1975 the interventions have been limited to cutting only the 30% largest trees. Individual trees were numbered and measured when the monitoring commenced in 1923 but the numbers were unfortunately lost by 1965, whereafter only data aggregated in diameter classes were collected. By the time the stand was due to be re-measured in 2017, new tree numbers and individual-tree measurements were introduced again. That is why only the data from the 2017 and 2021 surveys could be included in this study.

Densities in terms of the number of trees per hectare and basal area per hectare varied between the four plots and the two survey years. Considering the stand as a whole, basal area was reduced by 3.9 m² between 2017 and 2021 whilst the quadratic mean diameter (14.2 cm) and the basal-area percentage of *P. abies* remained constant at 82%. The growth dominance index, G_D (Binkley et al., 2006), indicating uneven-aged forest structure, has been moderately negative in all four plots of stand 9022. The value (in absolute terms) is lowest in plot 31 (−0.09) and largest in plot 34 (−0.23) with a stand index of −0.15. Apparently the stand has been successfully managed towards uneven-aged forest structure, but the final objective of a selection forest has not been met quite yet.

Stand 9082 is located at an altitude of 260 m asl and has a total area of 0.52 hectares. The stand origin probably was natural regeneration that occurred in the early 19th century. Starting in 1921, selection cuttings were introduced when Siljansfors Experimental Forest was established. Research monitoring commenced in 1959 and single-tree selection cuttings along with individual-tree measurements have been carried out approximately every 10 years between 1959 and 2021. During the first three interventions in 1959, 1969 and 1979 small gaps between 15 and 25 m were cut. Since 1990 an effort was made to work towards an equilibrium standing volume of 200 m³ ha^{−1} which was finally achieved in the last two survey years. Individual-tree measurements have been carried out in each survey year, but it was not until 2012 that ingrowth trees exceeding a stem diameter of 4.5 cm were numbered and measured individually. Unfortunately the 1959 survey

¹ The site index indicates site quality and is estimated as the mean total height of dominant *P. abies* trees at a base age of 100 years.



Fig. 1. Photo impressions of the stand structure at stands (A) Siljansfors 9022 and (B) Siljansfors 9082 near Mora in Central Sweden (60° 52' - 60° 55' N, 14° 19' - 14° 25' E) in September 2022.

data were not available to our analysis. The site index of this stand was estimated to be 24 m (Lundqvist, 1993).

In stand 9082, basal area has steadily increased between 1969 and 2021 from 18.0 to 28.2 m². A reduction in basal area has happened between 2012 and 2021, however, current basal area is markedly higher than in stand 9022. In the same way, the current number of trees per hectare and the quadratic mean diameter are higher in stand 9082 than in stand 9022. The basal-area percentage of *P. abies* has decreased over the years from 99% to 95%. In contrast to stand 9022, the growth dominance index, G_D has been strongly negative for stand 9082 right from the start and reached an (absolute) maximum in 1990 with a value of -0.34 . A low point was in 1979 with a value of -0.14 . For the last survey interval 2012–2021, $G_D = -0.21$. The growth-dominance index results suggest that size and growth structures typical of uneven-aged forest stands were successfully achieved and maintained throughout the monitoring period.

2.2. Demographic models

Since the end of the 19th century attempts have been made to identify quantitative rules for managing selection forests. The structure of such forests is often complex and cases of illegal logging but also silvicultural mistakes are generally more difficult to trace than in simple-structured plantations. At the same time forest managers noticed that selection forests more than any other form of CCF exhibited a stem-diameter structure that tends to take the shape of a (negative) exponential distribution. Colloquially such size distributions are often referred to as “reverse J” or “inversed J-shaped”. This observation quickly led to the hypothesis that such a diameter distribution was perhaps required to ensure the self-sustainability of timber resources within a single forest stand. French forester François de Liocourt was the first to propose a mathematical model that can describe the shape of this diameter distribution, which later became known as the law of de Liocourt (1898):

$$n = n_0 \times e^{-\lambda \times d} \quad (1)$$

In Eq. (1), tree size is represented by stem diameter, d . Model parameter n_0 is the initial number of trees for $d = 0$ or for infinitesimally small d whilst λ is a constant model parameter. Symbol e denotes the base of the natural logarithm and n_0 is the intercept, i.e. the point where the function crosses the ordinate. Eq. (1) should not be confused with the exponential distribution in statistics and rather more resembles functions describing decay processes over time, only that time is replaced by size. The de Liocourt model soon inspired forest managers to use Eq. (1)

as a basis for deriving appropriate thinning intensities and thinning cycles in selection forests so that the demographic processes required for self-sustainability were ensured (Pommerening, 2023).

Meyer (1933) discovered that the rate of frequency reduction in successive stem-diameter classes of the de Liocourt model (Eq. (1)) can be quantified by a single constant parameter q according to Eq. (2):

$$q = \frac{n_i}{n_{i+1}} = \frac{n_0 \times e^{-\lambda \times d_i}}{n_0 \times e^{-\lambda \times d_i + w}} = \frac{e^{-\lambda \times d_i}}{e^{-\lambda \times d_i} \times e^{-\lambda \times d_i \times w}} = \frac{1}{e^{-\lambda \times w}} = e^{\lambda \times w} \quad (2)$$

Here n_i and n_{i+1} refer to the number of trees in successive stem-diameter classes with d increasing from d_i to d_{i+1} . The class width of the empirical stem-diameter distribution is w , e.g. 4 cm in our study. Parameter λ can be interpreted as a relative growth rate (RGR) relating to the change in tree numbers with increasing size (Cancino and Gadow, 2002) whilst q is the tree-number equivalent to a growth multiplier (Wenk, 1994). However, for observed stem-diameter distributions, q is not constant but typically varies from diameter class to diameter class (Kerr, 2013; Pommerening, 2023).

The appeal of the de Liocourt model and the associated q factor is its simplicity, since largely only one parameter, the q factor, is needed to describe the whole model stem-diameter distribution (Hansen and Nyland, 1987). In principle, constant model q (also referred to as diminution factor) is a summary of complex information involving growth, mortality and resulting migration rates, i.e. the movement of trees between classes depending on their stem diameter. To the forest managers designing such demographic models, this dynamic information is often not available. Determining the parameters of the de Liocourt model (Eq. (1)) is not trivial, since they should reflect the aforementioned processes and as a result project a desired, future equilibrium stem-diameter distribution which does not yet exist. Some authors including Meyer (1952) have suggested simply applying nonlinear regression routines to observed, aggregated data for optimising model parameters n_0 and λ , but the results would only describe the current diameter structure of a given forest stand. Several alternative methods have been suggested for estimating n_0 and λ from a blend of data from both the current stem-diameter structure and possible future or ideal projections (e.g. Susmel, 1956; Poznański and Rutkowska, 1997; Cancino and Gadow, 2002; Pretzsch, 2009). Although these methods are easy to apply, the appropriateness of the results is uncertain.

The shortcomings of the de Liocourt and associated q factor model were addressed by several authors who instead proposed the use of dynamic demographic models (Prodan, 1949; Schütz, 2001, 2006; Brzeziecki et al., 2016; Kärenlampi, 2019). These model approaches have in common that they explicitly involve growth, mortality and

resulting migration processes. As such, dynamic demographic models are closer to the demographic processes underlying stem-diameter distributions. In these models, tree migration through size classes is a function of growth and mortality. Demographic equilibrium is achieved, if the number of trees growing into any diameter class i (ingrowth) equals outgrowth plus losses due to natural mortality and forest interventions according to Eq. (3).

$$\underbrace{n_{i-1} \times p_{i-1}}_{\text{Ingrowth from class } i-1} = \underbrace{n_i \times m_i}_{\text{Mortality in class } i} + \underbrace{n_i \times p_i}_{\text{Outgrowth towards class } i+1} \quad (3)$$

Here n_i is the number of trees in diameter class i , p_i is the outgrowth rate and m_i is the mortality rate pertaining to the same class. Both p_i and m_i result from model functions defining growth and mortality for each diameter class (Schütz, 2001, 2006). The outgrowth rate p_i is calculated from mean annual absolute growth rate, $(\delta d)_i$, as

$$p_i = \frac{(\delta d)_i}{w}, \quad (4)$$

where $(\delta d)_i$ and w are provided using the same unit, e.g. centimetre. Starting by inputting the number of trees in the largest diameter class, n_{\max} , all other n_i can be calculated iteratively based on Eq. (3) as

$$n_{i-1} = \frac{n_i \times (p_i + m_i)}{p_{i-1}}, \quad (5)$$

where $n_i = n_{\max}$ in the first step. Our research strategy was first to determine the dynamic demographic model of Eq. (3) and then to simplify this model by attempting to find a q factor equivalent (Eq. (2)).

2.3. Modelling growth

Following recommendations by Schütz (2001, 2006) absolute annual stem-diameter growth was modelled based on the concept of basal area of larger trees (BAL), i.e.

$$\delta d = a_0 + b_0 \times \text{BAL}^{c_0}. \quad (6)$$

In this context, BAL is the sum of cross-sectional areas of all diameter classes multiplied by the number of trees per hectare in each class that are larger than the diameter class under consideration, since only data aggregated in empirical diameter distributions were used. As such BAL is a cumulative measure of basal area and expression of the availability of resources such as light, nutrients and water (Wykoff, 1990). In Eq. (6), a_0 , b_0 and c_0 are model parameters. Annual absolute growth rate (AGR) of stem diameter is denoted by δd . We considered annual AGR irrespective of species, since the two stands were clearly dominated by *P. abies* (see Tables 1 and 2).

2.4. Modelling mortality

Mortality was modelled based on Eq. (7) with model parameters a_1 , b_1 , c_1 and diameter class d as dependent variable.

$$m = c_1 \times (d - a_1)^2 + b_1 \quad (7)$$

Table 1

Quantitative description of stand 9022 at Siljansfors Experimental Forest (Sweden) in survey years 2017 and 2022 of trees larger than 4 cm before cutting. N – density, calculated as number of trees per hectare, G – total basal area, calculated as the sum of cross-sectional tree stem areas at 1.3 m above ground, d_g – mean quadratic stem diameter at 1.3 m above ground level, G% *P. abies* – percentage of stand basal area, G , formed by *P. abies* alone, G_D – growth dominance index (Binkley et al., 2006). The stand is subdivided into four monitoring plots 31, 32, 33 and 34.

Plot	N [ha ⁻¹]		G [m ² ha ⁻¹]		d_g [cm]		G_D 2017–22	G% <i>P. abies</i>	
	2017	2022	2017	2022	2017	2022		2017	2022
31	1800	1464	31.0	24.4	14.8	14.6	-0.09	79	80
32	1416	1216	24.6	22.6	14.9	15.4	-0.11	73	71
33	2160	1932	28.2	23.5	12.9	12.4	-0.15	89	90
34	1508	1360	25.9	23.7	14.8	14.9	-0.23	88	85
Stand	1721	1493	27.4	23.5	14.2	14.2	-0.15	82	82

Table 2

Quantitative description of stand 9082 at Siljansfors Experimental Forest (Sweden) in six different survey years including trees larger than 4 cm before cutting. N – density, calculated as number of trees per hectare, G – basal area, calculated as the sum of cross-sectional tree stem areas at 1.3 m above soil level, d_g – mean quadratic stem diameter at 1.3 m above soil level, G% *P. abies* – percentage of stand basal area, G , formed by *P. abies* alone, G_D – growth dominance index (Binkley et al., 2006).

Survey year	N [ha ⁻¹]	G [m ² ha ⁻¹]	d_g [cm]	G_D	G% <i>P. abies</i>
1969	521	18.0	21.0	-0.30	99
1979	721	17.7	17.7	-0.14	99
1990	1054	22.0	16.3	-0.34	97
2000	1210	26.7	16.8	-0.21	97
2012	1167	30.8	18.3	-0.21	96
2021	1173	28.2	17.5	-	95

Similar to modelling growth as explained in Sect. 2.3, aggregated data were used here. The annual mortality rate m , i.e. rate $n_i^{(m)}/n_i$ with the number of dead trees, $n_i^{(m)}$, divided by the total number of trees, n_i , in class i , includes both natural tree mortality and tree mortality caused by human interventions. A slight complication of mortality modelling in demographic models for selection forests is that observed mortality in most cases does not reflect mortality of forests that are in a demographic equilibrium (Schütz and Pommerening, 2013). Therefore after fitting the model in Eq. (7) through nonlinear regression, parameters a_1 , b_1 , c_1 have to be fine-tuned manually so that they resemble a function of “future mortality” that increases more or less exponentially from low to large diameter classes. We carried out this task by processing information on mortality models used for demographic equilibrium models that were previously published in the literature (Schütz, 2006; Schütz and Pommerening, 2013).

2.5. Modelling n_{\min}

To model the demographic stem-diameter distribution correctly, particularly its precise location in relation to the ordinate, it is crucial to determine the number of trees expected to occur in the smallest diameter class, n_{\min} . This number should correspond to realistic recruitment conditions (Schütz, 2001, 2006). When assembling the final dynamic demographic model, input variable n_{\max} is optimised so that Eq. (5) eventually delivers the correct, pre-determined n_{\min} (Pommerening, 2023). Following the standard procedure in Central Sweden, we decided that the final stem diameter d_{\max} is 50 cm with target-diameter harvesting starting at 45 cm. For determining n_{\min} , Schütz (2006) proposed simulating different pairs of BAL and n_{\min} from Eq. (5) by inputting a number of arbitrary n_{\max} values into the dynamic demographic model after the finalised growth and mortality models have been implemented. These simulation results are overlaid by BAL- n_{\min} data from observations in different plots of the same forest stand or from one plot and different survey years. The former strategy was applied to the data of stand 9022 and the latter to the data of stand 9082. Both overlaid data point clouds can be described by separate trend lines and the point of intersection of these trend lines indicates n_{\min} and the corresponding

value of BAL.

2.6. Measuring change

The change in size structure over time can be measured in various ways. In Tables 1 and 2, we applied the growth dominance characteristic, G_D (Binkley et al., 2006), but it is also possible to use the simpler Gini index, \tilde{G} , (Lorenz, 1905; Gini, 1912) or the related coefficient of variation of stem diameters (Pommerening, 2023). For its convenient properties, we decided to apply the reciprocal of the Gini index, i.e. $G' = 1/\tilde{G}$. Characteristic G' is also known as the *homogeneity index* and was first proposed by de Camino (1976). This index can be estimated from aggregated data based on Eq. (8).

$$G' = \frac{\sum_{i=1}^{c-1} \sum_{j=1}^i \frac{n_j}{N}}{\sum_{i=1}^{c-1} \sum_{j=1}^i \frac{n_j}{N} - \frac{g_i}{G}} \quad (8)$$

The number of diameter classes is denoted by c whilst n_j and g_j are the number of trees and the basal area per hectare in class j . As in Tables 1 and 2, N and G are the stand number of trees and basal area, respectively. The homogeneity index can be calculated for both the demographic equilibrium model according to Eq. (3) and for the observed empirical diameter distributions. For the equilibrium model, G' should take values of approximately 1.0. The larger G' becomes, the more homogeneous the stand under study is and the further away is its size structure from the demographic equilibrium. Values of $G' \approx 10$ are, for example, known from homogeneous plantations that are regularly thinned according to the low-thinning type (de Camino, 1976).

2.7. Model efficiency

For evaluating the regression results we quantified efficiency, E , defined as

$$E = 1 - \frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}, \quad (9)$$

where \hat{y}_i is the i^{th} prediction (modelled stem-diameter growth or mortality rate), y_i is the corresponding i^{th} observation, n is here the number of observations and \bar{y} is the mean observation. Efficiency values approach one with increasing model performance. A value of zero indicates that the model explains no more variation than the mean value of the observations alone and negative values highlight biased estimates. For this analysis we used our own R code (R Development Core, Team,

2023).

3. Results

3.1. Growth analysis

The growth functions relating to the two stands at Siljansfors showed the typical behaviour expected from Eq. (6), where stem-diameter growth reaches a maximum at low values of BAL and gradually declines towards large values of BAL (Fig. 2). Large values of BAL are typical of small diameter classes and small values of BAL can be expected for large diameter classes. For stand 9082 (Fig. 2B), the growth curve declined more strongly with increasing BAL than that related to stand 9022 (Fig. 2A), which is indicated by the difference in parameter b_0 (Table 3).

Differences in site quality are expressed by the relative location of the two curves: The growth curve relating to stand 9022 is generally lower than that of stand 9082 which is consistent with the difference in site index previously measured (cf. Sect. 2.1). A quantitative expression of this difference is the intercept parameter a_0 (Table 3). The residual variance was larger for stand 9082 than for stand 9022, which is consistent with the lower efficiency measure, E , (Eq. (9), Table 3).

3.2. Mortality analysis

In both stands, mortality rates m (see Section 2.4) varied much over

Table 3

Parameters of the stem-diameter growth and mortality models underlying the dynamic demographic equilibrium models for stands 9022 and 9082 at Siljansfors Experimental Forest (Sweden). The parameters listed are those occurring in the equations given in the left column of the table.

Model	Parameter	9022	9082
Growth (Eq. (6))	a_0	0.23488	0.33997
	b_0	-0.00026	-0.00001
	c_0	1.88243	3.10286
	E	0.61488	0.27475
	Mortality (Eq. (7), regression)	a_1	10.54993
b_1		0.02457	0.01741
c_1		0.00009	0.00007
E		0.30171	0.26370
Mortality (Eq. (7), synthesised)		a_1	
	b_1		7.57290
	c_1		0.00300

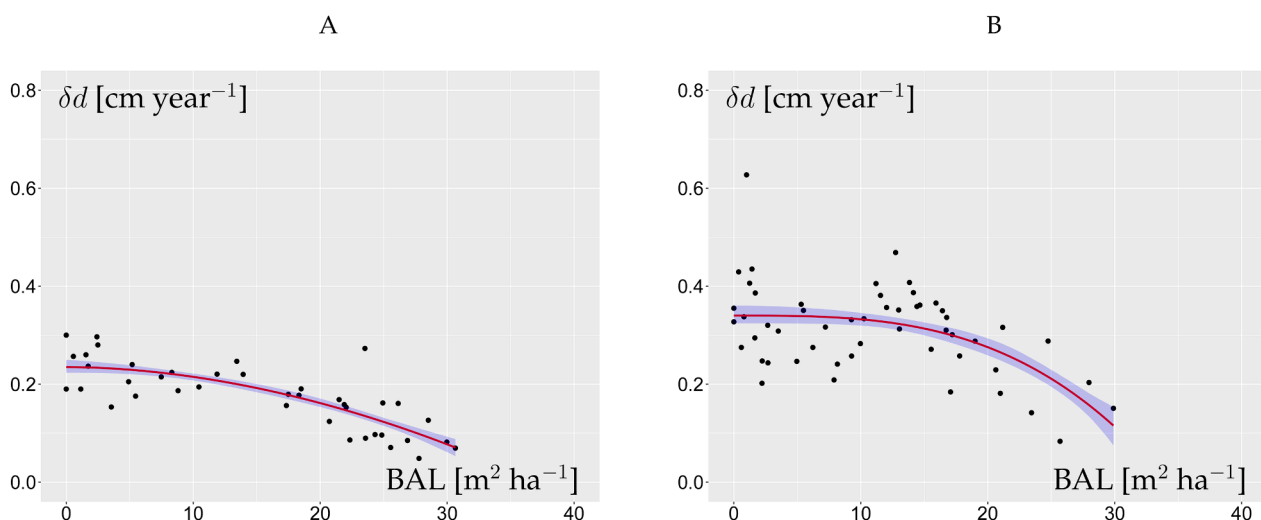


Fig. 2. Annual stem-diameter growth, δd , dependant on basal area of larger trees (BAL), cf. Eq. (6) along with the 95%-envelopes derived from the residuals through bootstrapping of stands (A) Siljansfors 9022 and (B) Siljansfors 9082 in Central Sweden.

the range of diameter classes. This variation may be partly explained by the fact that natural mortality and human interventions were summarised in one rate. The variation of m as shown by the data cloud, however, may also suggest that management has been somewhat inconsistent over the years.

For natural mortality, the function in Eq. (7) should typically display a U shape (Sterba and Monserud, 1999) and this pattern can clearly be recognised for both stands (Fig. 3, Table 3). However, much of the observed mortality, particularly in larger diameter classes, is the result of thinnings. Because of the variability of rates m , uncertainty was considerable in both stands. We have synthesised a realistic mortality function by merging the quantitative information obtained from observed mortality rates and from past mortality functions used in other published demographic equilibrium models, e.g. in Schütz (2001, 2006) and Schütz and Pommerening (2013). This is possible, since the cutting strategy in selection forests is universal. According to these publications, mortality should be lowest in small stem-diameter classes and then gradually increase in an exponential fashion. This pattern was easiest to implement for stand 9082. In stand 9022, mortality/interventions seemed a little too high in our judgement, especially since growth was less here than in stand 9082. Therefore we decided to apply the same mortality function to the demographic equilibrium models of both stands.

3.3. Determination of n_{\min}

In the case of our study, the linear function describing observed pairs of BAL and n_{\min} and the power function that formed the trend line of the simulation results intersected twice (Fig. 4). Since the first diameter classes, d_{\min} , used in the demographic models (2 cm and 6 cm, respectively) were rather small, we decided to settle for the intersection point at larger BAL. This was also supported by the observed data. These points of intersection provided $n_{\min} = 697.34$ and $n_{\min} = 322.89$ for stands 9022 and 9082, respectively (Fig. 4). Through optimisation using the demographic model as a function, optimised $n_{\max} = 0.77301$ and $n_{\max} = 2.24186$ were obtained for the two forest stands. These are the required final inputs to get the demographic model started.

3.4. Demographic equilibrium models

A comparison of the dynamic demographic models fitted for stand 9022 with the observed, empirical stem-diameter distributions revealed that deviations existed particularly for the medium diameter range, i.e.

classes 6–18 cm, the mid-storey (Fig. 5). This deviation was greatest in plots 31 and 32 and smallest in plot 33. The changes in the stem-diameter distribution were marginal between 2017 and 2022. In terms of the smallest diameter class, the distribution has changed to the worse in plots 31, 32 and 34 between the two years. This is contrasted by the stem-diameter distribution in plot 33, which has improved as a whole between 2017 and 2022.

The regression results in Table 4 indicate that the dynamic demographic model of Eq. (3) can be well expressed by the simpler de Liocourt model (Eq. (1)), provided the diameter range is split into two different ranges with one class overlapping. The overlap of the two diameter ranges ensures a smooth transition from one set of model parameters to the other. Correspondingly, the dynamic demographic model can be summarised by two q factors, i.e. $q = 1.4$ for smaller and $q = 1.7$ for larger diameter classes (Table 4).

In contrast to stand 9022, the empirical stem-diameter distribution relating to stand 9082 revealed a small deviation from the dynamic demographic model (Fig. 6) for the years 1990–2021. Even for the mid-storey (involving diameter classes 10–34 cm) the deviation was near zero between 2000 and 2021. There was even a small surplus of trees in most classes of this diameter range. The graphical comparisons suggested that stand 9082 possibly has experienced management treatments that were more appropriate than those applied in stand 2022. This plausible explanation was previously indicated by the growth dominance index, see Section 2.1 and Tables 1 and 2.

The situation in 2021, as given by the comparison of stem-diameter distributions, suggests that stand 9082 has reached its theoretical demographic equilibrium.

For stand 9082, it was also possible to express the dynamic demographic model by two simpler de Liocourt models on the condition that again two diameter ranges were considered separately with one diameter class of overlap (Table 4). The diameter ranges of these two models differed from those that were best for stand 9022, but the two q factors were quite similar to those of stand 9022, i.e. $q = 1.3$ for smaller and $q = 1.7$ for larger diameter classes.

In both stands, the homogeneity index, G' (Eq. (8)), of the dynamic demographic model was a little less than 1.1 and had nearly the same value (Fig. 7). Apparently our results met the expectation given by de Camino (1976) well. Most values of G' relating to the empirical stem-diameter distributions were considerably less than this theoretical model reference with the exception of plot 31 of stand 9022 in 2017. The homogeneity index suggested that the structure of both stands has been

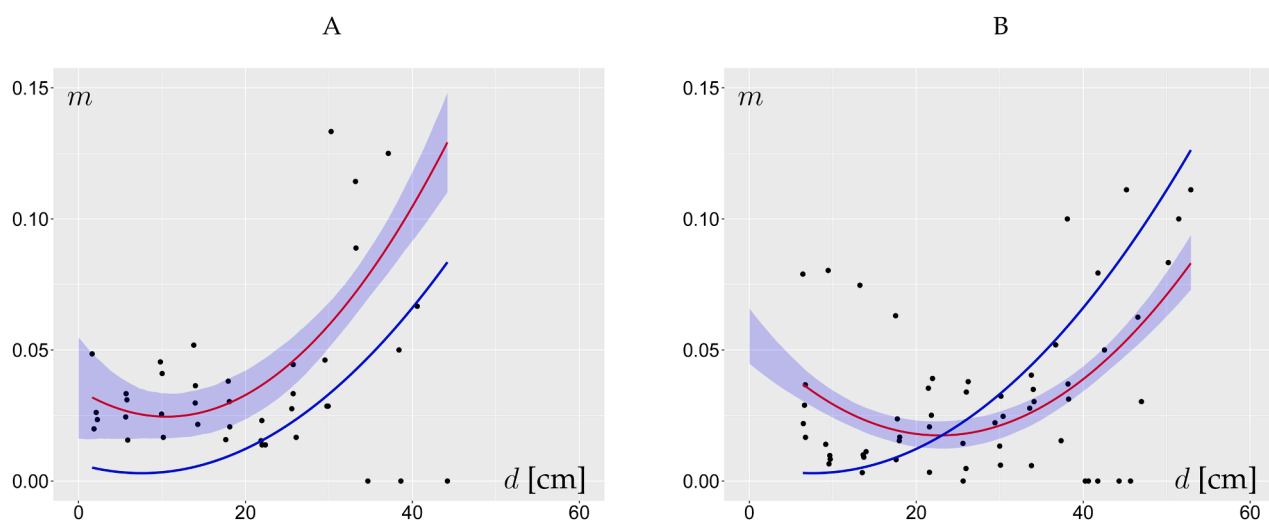


Fig. 3. Annual mortality rates, m (see Section 2.4), dependent on stem diameter, d , cf. Eq. (7) along with the 95%-envelopes derived from the residuals through bootstrapping of stands (A) Siljansfors 9022 and (B) Siljansfors 9082 in Central Sweden. Red curve: Trend curve of observed mortality rates. Blue curve: Synthesised mortality rates. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

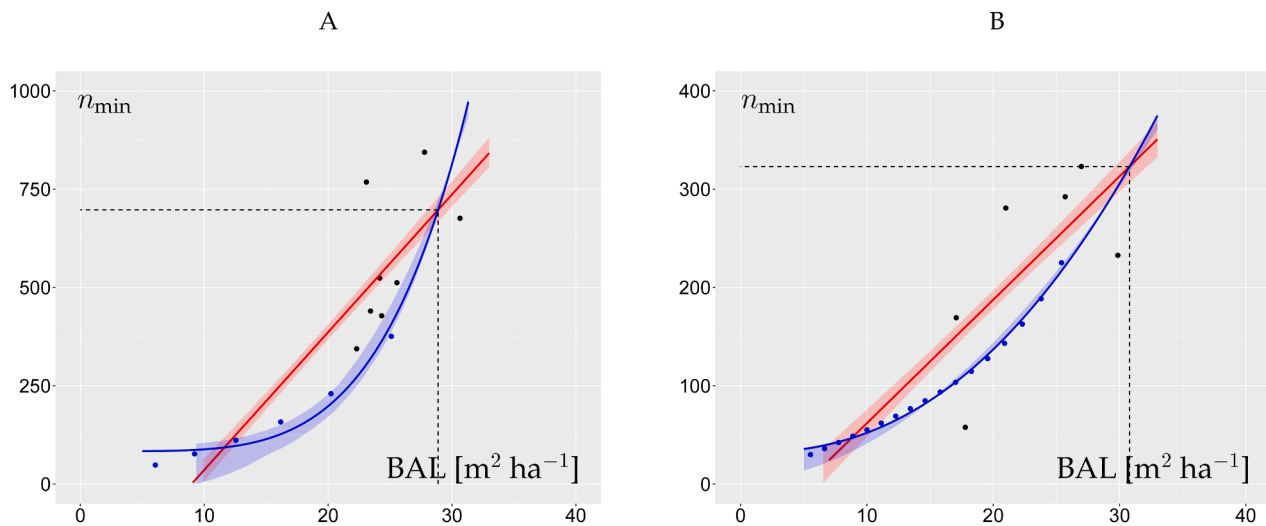


Fig. 4. Black data points: Pairs of values of basal area of larger trees, BAL, cf. Eq. (6) and the number of trees in the smallest diameter class, n_{\min} , observed in different plots (stand 9022, A) or in the same stand at different times (stand 9082, B) along with the linear trend curve (red). Blue data points: Pairs of values of BAL and n_{\min} simulated by inputting a number of arbitrary n_{\max} values into the demographic model after the finalised growth and mortality models have been implemented. The corresponding trend curve follows a power function of the form $n_{\min} = a_2 + b_2 \times \text{BAL}^2$ and is given in blue. In both cases, the 95%-envelopes were derived from the residuals through bootstrapping. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

exceptionally inhomogeneous throughout the plots and years.

Fig. 7(A) suggests that the empirical diameter distribution of plots 31, 32 and 34 are particularly close to the demographic model, whilst the visual impression of Fig. 5 rather indicates that the diameter distributions of plots 31 and 33 are closest. Fig. 7(B) appears to show that the diameter structure approached that of the model with increasing years, which was previously hinted by the growth dominance index (Table 2). There was a slight exception from this trend in 2012, when the number of trees in the lowest diameter classes was comparatively low. Overall the homogeneity index supports the view that both forest stands at Siljansfors are close to the ideal structure of a selection forest.

4. Discussion

Judging the current state of a selection forest has always been a challenge for both forest practitioners and researchers. Such an assessment is typically carried out on the basis of size structure. In combination with information on growth and mortality processes, structural analyses offer a good understanding of demographic processes in different size classes and thus of sustainability (Schütz, 2001, 2006; Schütz and Pommerening, 2013). This was the analysis strategy we pursued in our study. The two forest stands analysed were interesting for four reasons: (1) In contrast to classic selection forests in Central Europe, they mainly included only one species, i.e. *P. abies*. (2) Another unusual property of the selection forests at Siljansfors was the low final diameter of 50 cm with target-diameter harvesting starting at 45 cm. In general, low target diameters are common for this species in Sweden, however, 45–50 cm is comparatively low for traditional selection forests. (3) This study was also interesting considering that the two Siljansfors stands were geographically far beyond the traditional area where selection systems are practised and (4) they were maintained at a time when CCF in general was not believed to be a forestry model suitable to Sweden.

There were several reasons for the final stem diameter of 50 cm. The selection cuttings were carried out by standard harvesters and these machines were unable to process trees larger than 50 cm. Also, at Siljansfors, the risk of windthrow and bark beetle infestations usually steadily increases with tree size. In addition, growth and regeneration processes are generally much slower at these latitudes and as a consequence *P. abies* stands are believed to require lower densities at

Siljansfors compared to sites in Central Europe.

Diameter growth showed quite normal behaviour in our analysis and confirmed the differences in site quality and carrying capacity that were reported earlier (Fig. 2). Similar to previous research, BAL turned out to be a reliable predictor of growth in both cases. Mortality rates were also straightforward to establish and the modelling of future equilibrium rates presented challenges that were known from previous work (Schütz and Pommerening, 2013; Fig. 3). The mortality analysis of stand 9022 revealed signs of interventions that were perhaps too heavy in the past. When modelling the number of trees in the lowest stem-diameter class, n_{\min} , we found that these numbers of 697 and 323 trees per hectare were quite high compared with other models (Schütz, 2001, 2006; Schütz and Pommerening, 2013; Brzeziecki et al., 2016) which can be explained by the low diameter class which was selected as first class and by the comparatively large mortality rates in the mid-storey diameter classes. Over the years, achieving such high numbers of small trees has not been a problem at Siljansfors and that this is possible is confirmed by the observed empirical diameter distributions (Figs. 5 and 6).

The graphical comparison of observed stem-diameter distributions and demographic equilibrium models revealed that stand 9022 at Siljansfors has not yet reached the desired size structure, which could be the result of the frequent removal of small to medium-sized trees in the first half of the monitoring period (Fig. 5). In stand 9022, the mid-storey range of stem diameters (6–18 cm) has deficits that can be improved by increased fellings of trees in classes 26–30 as a “quick fix”. A similar approach was successfully implemented in a *P. abies* selection forest in the Harz mountains in Northern Germany (Peterson and Guericke, 2004). Another, more long-term strategy that might be preferred by forest owners is to simply continue with the target-diameter fellings typical of selection forests and to wait until a more balanced demographic structure will establish itself naturally with progressing size cohorts. An improvement of size structure does not seem to be necessary in stand 9082. Here target-diameter harvesting appears to be sufficient to maintain a sustainable demographic structure. Stand 9082 has apparently gained much from an appropriate management of recent decades. These findings are largely supported by the homogeneity index, G' (Eq. (8), Fig. 7). The index values were exceptionally low, indicating a high degree of structural inhomogeneity. For equilibrium models, de Camino (1976) stated that G' should take values not far from 1.0, often between 1.3 and 2.8. Our analysis has also confirmed that it is always a

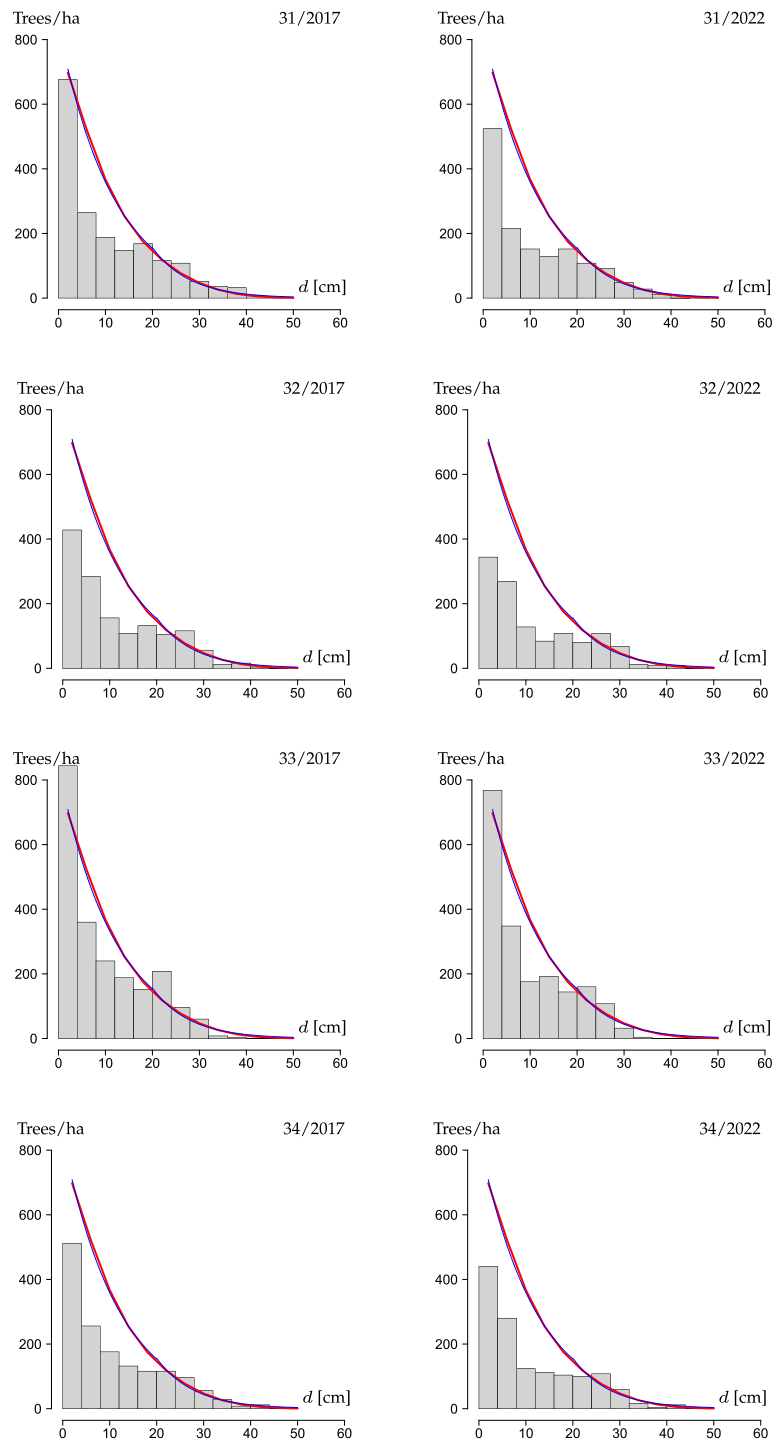


Fig. 5. Empirical stem-diameter distributions (histograms) and demographic equilibrium models (curves) of plots 31, 32, 33 and 34 of stand 9022 in 2017 and 2022. Blue curves: Demographic equilibrium model (Eq. (3)). Red curves: de Liocourt model (Eq. (1)). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

good idea to consider multiple criteria in the assessment of size structure rather than only one. The comparison of graphical (Figs. 5 and 6) and index results (Fig. 7) have clearly helped to arrive at balanced conclusions. Based on these results we need to reject our initial hypothesis that the structure of the two stands at Siljansfors is very different from that of a selection forest at equilibrium.

Our analysis also revealed that it is possible to simplify the dynamic demographic model of Eq. (3) by the de Liocourt/ q -factor model Eqs. (1) and (2). The latter has in the past often been criticised for the fact

that it is a static model (and as such not explicitly considers growth and mortality processes), but also for the assumption that q is constant throughout the diameter range (Hanewinkel, 1998; Schütz and Pommerening, 2013). In addition, procedures proposed for estimating q from current observations (Susmel, 1956; Poznański and Rutkowska, 1997; Pretzsch, 2009) have cast doubts (Hanewinkel, 1998; Pommerening, 2023). Therefore it is interesting to verify the de Liocourt/ q -factor model with a more explicit demographic approach such as that of Eq. (3). Even better possibly is the option to derive de Liocourt/ q -factor

Table 4

Parameters of the de Liocourt model (Eq. (1)), efficiencies, E (Eq. (8)) and q factors (Eq. (2)) for stands 9022 and 9082 at Siljansfors Experimental Forest (Sweden) that correspond to the dynamic equilibrium model (Eq. (3)) in the stem-diameter ranges d .

Stand	d range	de Liocourt model parameters	E	q
9022	[02, 22]	$n_0 = 839.68392$, $\lambda = 0.08490$	0.99736	1.40440
	[22, 50]	$n_0 = 1981.56793$, $\lambda = 0.12702$	0.99384	1.66210
9082	[06, 30]	$n_0 = 502.18765$, $\lambda = 0.07260$	0.99945	1.33696
	[30, 50]	$n_0 = 2580.76155$, $\lambda = 0.12910$	0.99320	1.67598

models directly from dynamic models in an attempt to offer a simplified model version that can more readily be applied in forest practice. In this study, the strategy of expressing a more complex, dynamic demographic model by the simpler de Liocourt/ q -factor model succeeded. However, q was definitely not constant throughout the whole diameter range but it was necessary to define two different stem-diameter ranges in order to capture the complexity of the dynamic model. A similar requirement has previously been reported in the literature, for example, by Hett and Loucks (1976) and Hansen and Nyland (1987). These authors suggested the use of decreasing q factors with increasing diameter class from small to large. Our research, however, suggested the opposite, i.e. slightly smaller q factors in the smaller diameter ranges followed by larger q factors in the larger size range. From a methodological point of view, splitting the diameter range and fitting two separate Liocourt/ q -factor models for each stand along with one diameter class overlapping both ranges appears to be a straightforward way of expressing high complexity in terms of a simple model.

5. Conclusions

Our study has shown that it is possible to establish and maintain selection systems in more or less mono-species *P. abies* forests in Central Sweden. The demographic structure necessary for this silvicultural system has been accomplished largely with a single species and with target diameters that are much smaller than in traditional Central European selection forests. This is an experience that is also of great value to forestry representatives of selection forestry working in areas where this management has a long history. The two stands at Siljansfors are a remarkable and valuable exception in a country where otherwise rotation forestry prevails. Both stands are already frequently used as CCF management demonstration areas and it is likely that now, with the introduction of this management type in Sweden, they will feature even more often in training and research. For this purpose it is also useful to know that the dynamic demographic model can be converted to a q -factor model that is easier to apply in forest practice as shown in this study. Both model approaches are helpful tools for assessing the sustainability of ongoing forest management.

Author contributions

A.P. and L.O. conceived the project idea and designed the methodology. L.O. and O.L. selected the selection stands. L.O. and O.L. collected recent tree data in stand 9022. O.L. organised the last surveys in stands 9022 and 9082 and is responsible for the data curation. A.P. and L.O. wrote the first manuscript draft. O.L. supplied information on stand history and treatments and commented on various drafts of the text.

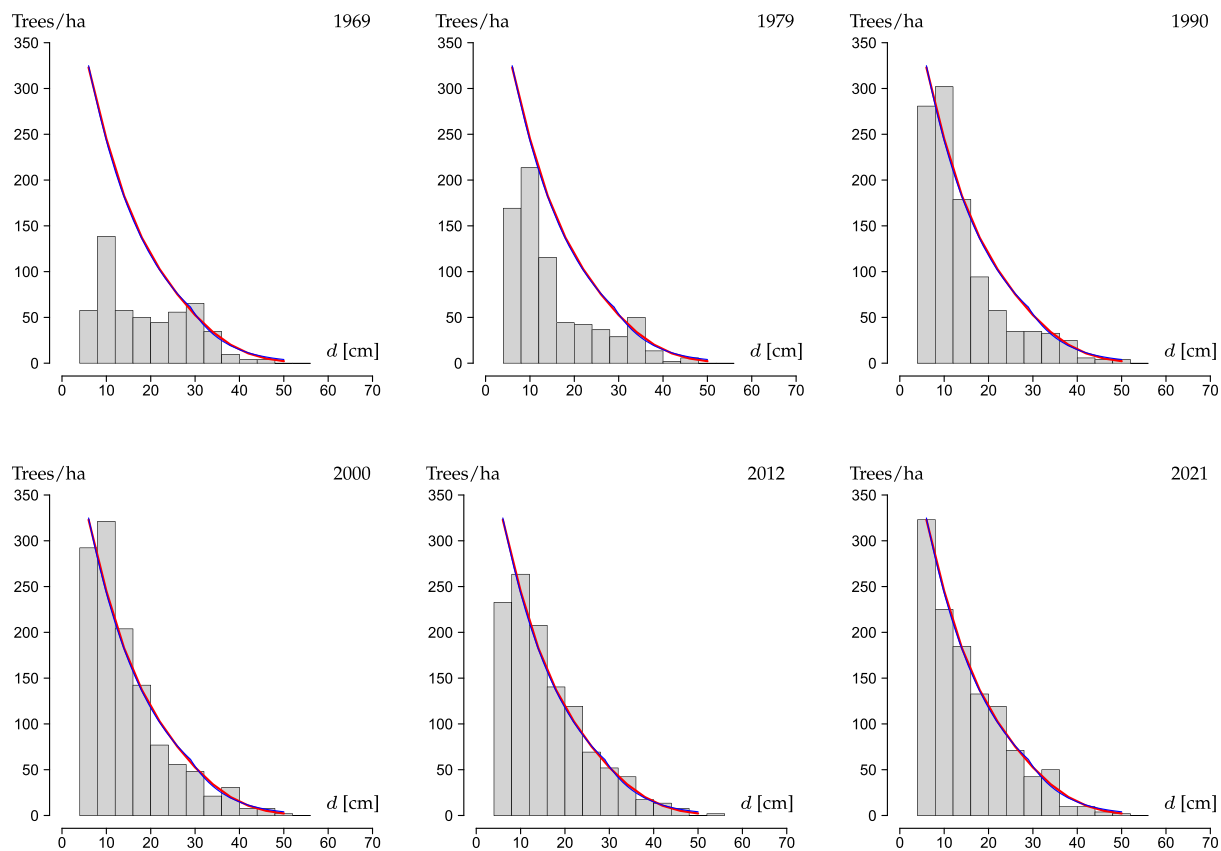


Fig. 6. Empirical stem-diameter distributions (histograms) and demographic equilibrium models (curves) of stand 9082 between 1969 and 2021. Blue curve: Demographic equilibrium model (Eq. (3)). Red curves: de Liocourt model (Eq. (1)). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

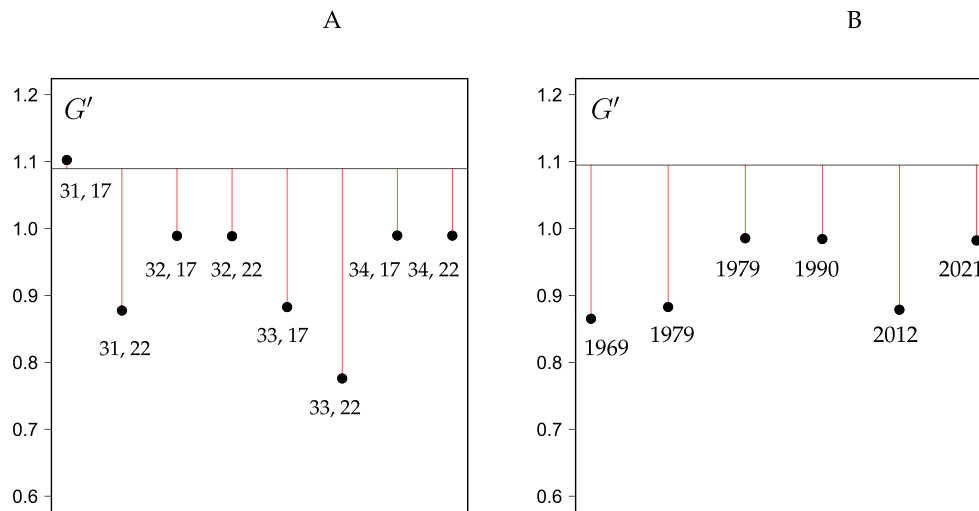


Fig. 7. Homogeneity index, G' , by de Camino (1976) (Eq. (8)) for stands Siljansfors 9022 (A) stand 9082 (B) in Central Sweden in different plots (A) and years (A, B). The black horizontal line marks the reference value of the dynamic demographic model (Eq. (3)), i.e. $G' = 1.0936$ for stand 9022 and $G' = 1.09483$ for stand 9082. The x axis has no particular scale here.

Declaration of Competing Interest

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.

Data availability

The data used in this study can be accessed through the Silvaboreal portal on <https://www.silvaboreal.com/>.

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