Relative density and competitive dynamics of Scots pine (*Pinus sylvestris* L.) forests in western Italian Alps

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Abstract: Forest stands with a major Scots pine (*Pinus sylvestris* L.) component occupy more than 28,000 hectares in the western Italian Alps. The aim of this research is to analyze the intensity of competition for available resources and to describe past and actual dynamics of Scots pine stands. Data from a regional forest inventory provided the basis for the description of maximum achievable competition by means of Reineke's Stand Density Index. At a stand scale, tree data from three 0.5-ha permanent plots were analyzed to study ongoing self-thinning dynamics by means of relative density computation and characterization of live and dead tree size distributions.

Keywords: *Pinus sylvestris* L., Competition, Self-thinning, Stand Density Index, Relative density.

1. Introduction

Scots pine (*Pinus sylvestris* L.) is the most widespread pine species in Europe (figure 1), covering more than 20 million hectares (20% of total forested area). It occurs on a variety of soils and in extremely diverse climates, and is therefore differentiated into many varieties or ecotypes (Białobok 1970).

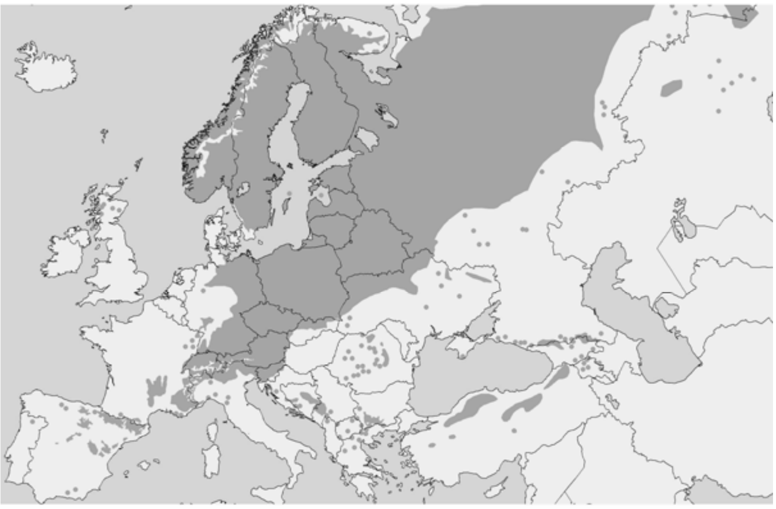


Fig. 1: Range of *Pinus sylvetris* L. in Europe (from Csaba et al. 2003).

Scots pine is a light demanding, usually early seral species that can establish both in acid and limestone soils (Richardson 2000). Scots pine forests often occur on coarse-textured soils that, even in regions of high rainfall, can be comparatively dry; Scots pine can withstand dry conditions better than all other indigenous tree species, including oaks (Ellenberg 1988).

In the western Alps Scots pine has a wide altitudinal range (from the Po plain at 100 m a.s.l to the valleys up to 2000 m a.s.l) and climatic distribution, encompassing both the external Alps with an average annual rainfall of more than 2000 mm and the internal, continental valleys with an average annual rainfall ranging between 500 and 600 mm (Richardson 2000). The role of this species varies in different environments:

- In the Po plain it was introduced more than 200 years ago and now is more or less naturalized as a pioneer species in the coarse-textured soils, where it can be very competitive.

- In the external-intermediate sectors of alpine valleys it is usually a pioneer species that has been favoured by past fires (Gobet et al. 2003), heavy forest cuts, and by the recent increase of fallow lands (Farrell et al. 2000; Krauchi et al. 2000). After centuries of heavy human influence in a large part of the present stands the succession from Scots pine to other definitive broadleaves and conifers is very slow.

- The internal (continental) sectors of the alpine valleys are the only sites where Scots pine could be considered stable (Ozenda 1985). In this environment this pine is both the early seral and late seral species because in these dry condition (less than 700 mm year^{-1} rainfall) it is a strong competitor with respect to the other conifers.

With increasing population density and pressure from tourism in mountain environments, the protective role of these forests is becoming the primary forest function (Krauchi et al. 2000). The growing demand for environmental and recreational services from the forest requires a deep knowledge of the dynamics regulating stand stability and vegetation development over time.

This paper aims to provide a quantitative assessment of Scots pine forests dynamics in the Southwestern Italian Alps. The self-thinning rule is a widely accepted model depicting the inverse-proportional relationship between plant mean size (or biomass) and stand density. The maximum stand density achievable for mean individual size is plotted by an exponential function (Reineke 1933; Yoda et al. 1963). Comparing observed stand density against the theoretical maximum expressed by the self-thinning line, one can easily assess the competition dynamics acting in the stand and predict their outcome in terms of tree mortality (Long 1985). Determination of the self-thinning line on a species basis and application of a relative density index can be considered important steps towards a greater understanding of population and stand dynamics and of the role of intraspecific competition in tree mortality.

2. Materials and methods

The study area is represented by Piemonte and Valle d’Aosta regions in Northwestern Italy (fig. 2). According to the last regional forest inventories (I.P.L.A. 2003b, 2004) pure Scots pine stands occur on 28,000 ha, on elevations ranging from 300 to 1600 m. Most pine forests occupy the more continental, inner sectors of alpine valleys; relic stands can be found on former peatlands in the northeastern lake district.

Fig. 2: Study area, Piemonte and Valle d’Aosta regions.

At a regional scale, the overall intensity of competition was described by means of the Stand Density Index (Reineke 1933), a measure based on the relationship between quadratic mean diameter *QMD* and number of stems *N* per unit area in pure even-aged stands. SDI describes density by calculating the number of stems per hectare related to a 25 cm mean diameter (Daniel et al. 1979):

$$(1)\quad SDI = N\left(\frac{QMD}{25}\right)^{b}$$

A species' maximum SDI represents the boundary of all possible size-density combinations, i.e. the maximum attainable density for trees of a given size. The ratio between observed stand density and this theoretical maximum describes the competition dynamics acting in the stand and predicts their outcome in terms of tree mortality (Drew and Flewelling 1979; Long 1985). Stands with the same relative density share many fundamental population-level attributes, including self-thinning, canopy closure, mean live crown ratio, and growth-growing stock relationships (Jack and Long 1996); different relative density thresholds have been suggested to indicate crown closure, initiation of competitive dynamics, and the onset of self-thinning (Drew and Flewelling 1979; Long 1985).

The coefficient *b* assumes a constant value of 1.6 for pure and even-aged stands of any species, age, and site fertility, according to Reineke (1933). This idea has been thoroughly discussed in an impressive amount of literature (e.g., Weller 1987; Lonsdale 1990; Hynynen 1993; Zeide 1995; Pretzsch and Biber 2005). Moreover, the biological mechanisms underlying the self-thinning process as well as the constancy in shape of the self-thinning line across all of the stand's developmental stages are still under debate (Zeide 2004; Reynolds and Ford 2005). Still, estimating the intensity of competition within a stand by relating its current SDI with the maximum value detected for the species should provide consistent results whatever the exact formulation of the self-thinning equation might be.

A regional forest inventory (I.P.L.A. 2003b, 2004) provided the data necessary for the calculation of relative density in Scots pine stands. The inventory was based on temporary circular plots (radius between 8 and 15 m according to overstory density). For each plot, stand-level variables were recorded, such as geographic coordinates, elevation, average slope, forest cover type, stand structure and developmental stage, percent canopy cover, and many others. Species and dbh of all living individuals bigger than 7.5 cm in dbh were recorded. The analysis was run according to the following steps:

a. Only pure (>70% of total BA provided by Scots pine), even-aged, non-managed plots were selected; a stand was considered managed if total number of stumps exceeded 10% of total living trees. A total of 245 plots were selected for further analysis.

b. We chose to represent the self-thinning boundary as a log-linear relationship between average mean diameter and density. These variables were calculated for each stand and represented on a log-log scatterplot. Reineke's SDI (equation 1) was calculated for each plot, assuming a constant self-thinning coefficient of -1.6.

c. Maximum SDI was assumed to be the 98th percentile of the SDI frequency distribution; higher SDI can be attained by extremely dense sample plots (or due to sampling errors), but the stand's and species' SDI has generally a less extreme value. Analysis of known SDI_{max} values and inventory data for several forest species in the Western US showed that the 98th percentile of the SDI distribution is usually a reliable threshold for SDI_{max} estimation at the stand or population level (Shaw, personal communication).

d. An estimate of overall competition intensity in the stands was obtained by calculating their relative density (SDI/SDI_{max}).

e. To test for a variable slope, a new regression line was fitted between the most crowded stands. To ensure that only stands actually undergoing self-thinning were selected, a minimum threshold of RD = 0.70 was maintained (Solomon and Zhang 2002), both including and excluding the "tail" of the SDI distribution. The slope of the new self-thinning line was then compared with Reineke's slope (-1.6) at a 95% confidence level.

The reference conditions represented by SDI_{max} were then compared to the competitive dynamics at a stand level. Three permanent sample plots (70x70 m) were established during summer 2005. All the standing live and dead trees (dbh >2.5 cm), along with stumps and logs bigger than 10 cm in base diameter, were labelled and mapped on x,y axes. For each individual, species, dbh, total height, crown ratios and crown radii in four orthogonal directions were recorded. Tree coordinates and measurements were stored in a spatial database (ArcGIS 8.3).

n	*Location*	*UTM*	*Elevation [m]*	*Slope.*	*Aspect*	*Age*
1	S. Maria Maggiore (VB)	5110657 N 457763 E	1050	40%	E	30
2	Toceno (VB)	5110964 N 458567 E	1050	80%	W	90-130
3	Trasquera (VB)	5118744 N 439503 E	1247	30%	SE	100-300

Table 1: Overview of permanent sample plots used in this study. Age of the stands was inferred from available documentation and forest management plans.

SDI of the permanent plots was calculated both by Reineke's formulation and by summation (equation 2) of each tree's contribution to overall stocking (Stage 1968; Shaw 2000):

$$(2)\quad SDI_{sum} = \sum_{i=1}^{n} \left(\frac{d_i}{25} \right)^{1.6}$$

where d_i is the diameter at breast height of tree *i*.

Relative stand density (SDI/SDI_{max}) arising from both methods was computed. The information about competitive dynamics provided by relative density was related to the stands' history and actual structure. Stand structure was described in the permanent plots by measures of average size, density and canopy cover. Dbh distribution of live and dead Scots pine trees were examined to detect mortality trends. Within-stand size heterogeneity, that is an outcome of asymmetric competition, i.e., arising from light resource availability (Weiner and Thomas 1986; Rouvinen and Kuuluvainen 2005) was computed by the Gini coefficient (Weiner and Solbrig 1984):

$$(3)\quad G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \left| d_i - d_j \right|}{2n(n-1) \cdot QMD}$$

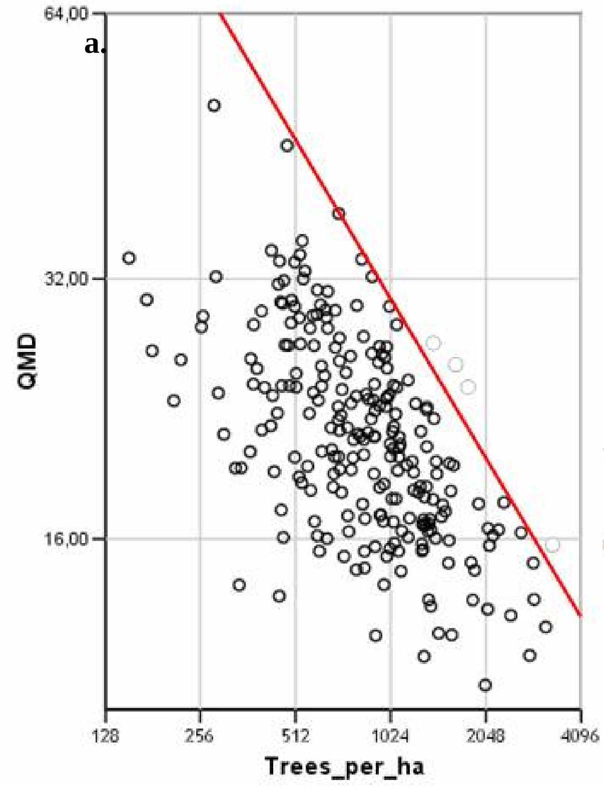
where *n* is the total number of trees, *d* their diameter at breast height and *QMD* the quadratic mean diameter of the stand. *G* values are constrained between 0 (all individuals are equal) and 1 (maximum heterogeneity).

3. Results

3.1. Regional analysis of competition

Maximum calculated SDI for Scots pine stands in the sample is 1373 (figure 3a). Four plots had higher SDI, representing 99th and 100th percentiles of the SDI frequency distribution, and were discarded from the stand-level estimate. The range of relative densities (RD) in the sample is between 0.06 and 1.00. In most stands (48%) RD ranges from 0.35 and 0.60, and 25% of the stands have a RD greater than 0.60 (figure 3b).

The slope of the self-thinning lines that were fitted by ordinary least squares regression between QMD and density of the stands with RD >0.70 were -1.65 and -1.51, respectively including or excluding from the subsample the plots with $SDI > SDI_{max}$ ($R^2 = 0.95$ and 0.94 respectively). In both cases, the confidence envelope for the new slope included Reineke's value of -1.6 ($p < 0.05$). Reineke's slope was used in the following analyses.



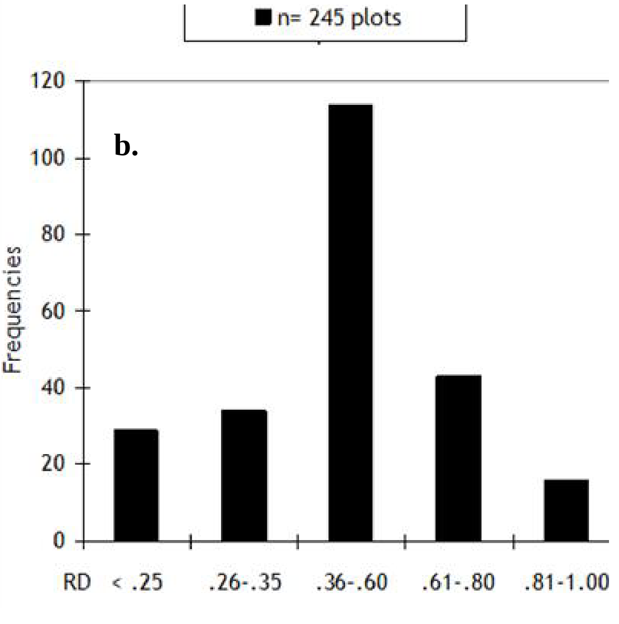


Fig. 3a (left): Self-thinning line for pure, even-aged *Pinus sylvestris* L. stands in the study area. QMD in cm.
Fig. 3b (right): relative density frequency distribution for $SDI_{max} = 1373$. RD intervals according to Long (1985).

The three permanent plots were characterized by different densities, age and history (figure 4); the main stand parameters are summarized by table 2. Plot 1 is a dense, young Scots pine stand established on a previously non-forested slope. Mature stands in the higher part of this valley are the seed source for seedling establishment on this former meadow starting about 30 years ago, most likely after the abandonment of farming and grazing practices. Density is 945 trees ha^{-1}, (basal area: 40 m^2 ha^{-1}, canopy cover: 91%). QMD is 23.2 cm and dominant height is 16.1 m. Stand Density Index is 837 (Reineke's method) or 804 if computed by summation. Relative density is 0.61 and 0.59 for the two SDI formulations respectively.

Plot 2 is located on a similar site on the opposite side of the same catchment. It is a nearly pure Scots pine stand with 838 trees ha^{-1} (basal area: 71.6 m^2 ha^{-1}, canopy cover: 78%). QMD is 33 cm and dominant height is 21.1 m. Available management plan and field evidence (tapping scars for resin production, which stopped after World War II) suggest the stand is at least 90-120 years old. SDI is 1307 (1259 by summation), with a relative density of 0.95 (0.92 as computed with the summation method).

Plot 3 is characterized by a lower density (597 trees ha^{-1}, basal area: 34.2 m^2 ha^{-1}) and less canopy cover (75%). Quadratic mean diameter is 27 cm (dominant height: 22.7 m). The structure is markedly two-storied, with a sparse mature overstory and dense regeneration patches establishing in the gaps. European larch (*Larix decidua* Miller) and Norway spruce (*Picea abies* (L.) Karst.) account respectively for 10% and 7.6% of total number of plants, and concentrate almost exclusively in the smallest size classes. Tree cores from mature Scots pines in the stand (Motta et al. 1999) were found to be up to 300 years old. The stand was disturbed in the last 20 years by repeated selective loggings. SDI is 674 (581 by summation); relative stand density is 0.45 (0.42 as computed with the summation method).

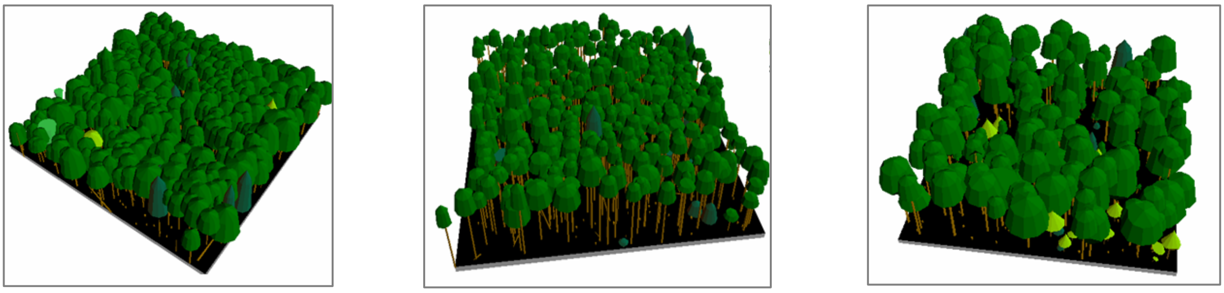


Figure 4: Visual representation of permanent plot 1 (S. Maria), 2 (Toceno) and 3 (Trasquera), from left to right.

n	*Location*	*Age*	*Trees ha^{-1}*	*G ha^{-1} [m^2]*	*Cover*	*QMD [cm]*	*Height$_{top}$ [m]*	***RD***	***RD$_{sum}$***
1	S. Maria Maggiore	30	945	39.9	91%	23.2	16.1	**0.61**	**0.59**
2	Toceno	90-130	838	71.6	78%	33	21.1	**0.95**	**0.92**
3	Trasquera	100-300	597	34.2	75%	27	22.7	**0.45**	**0.42**

Table 2: Stand parameters and relative density (both calculation methods) of the permanent plots.

Results of dbh distribution analysis (figure 5) show that plots 1 and 2 are characterized by an unimodal, symmetric size distribution, while plot 3 has a distinct bimodal pattern, mainly due to the regeneration patches established in recently formed gaps. Skewness of the dbh distribution (Scots pine only) is -0.12, 0.17 and 0.39 respectively. Gini coefficients vary from 0.20 in the first stand, to 0.14 in the second and 0.44 in the third, expectedly marking the greater size differentiation in the two-storied stand.

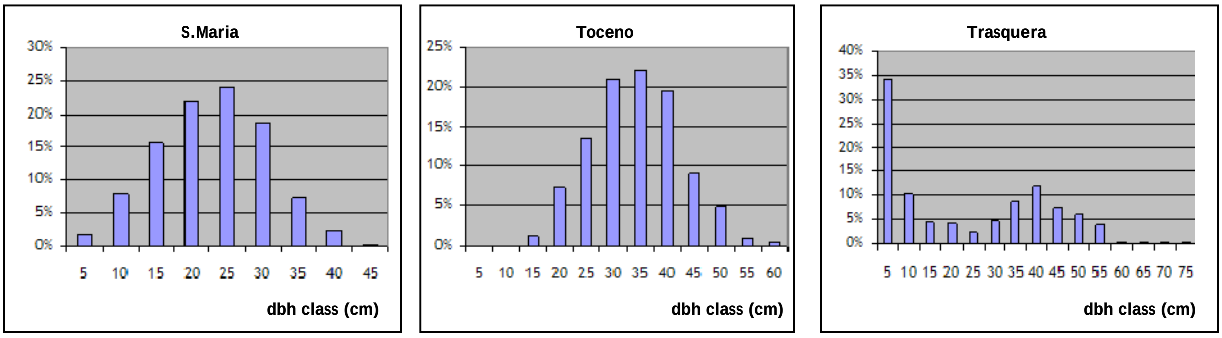


Figure 5: Scots pine dbh distribution in permanent plots 1-3 (left to right). On the x-axis, DBH classes in cm.

Mortality is concentrated on smaller size classes in plots 1 and 2, but is more diffuse in plot 3. The number of dead trees is 248, 103 and 104 per hectare respectively, with corresponding mortality ratios of 20.0%, 14.4% and 14.8%. Snags are the main contribution to coarse woody debris in the lower size classes; stumps account for most of the mortality in the upper classes (figure 6).

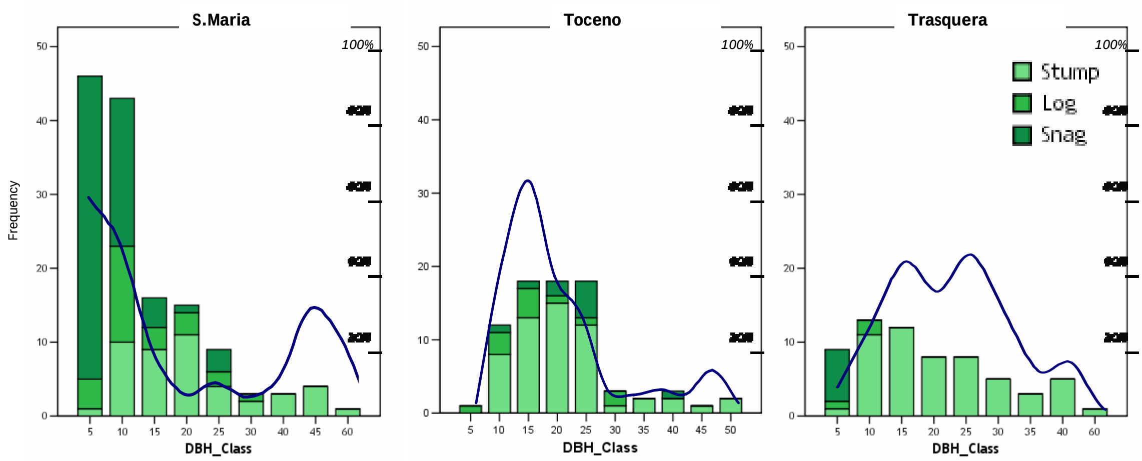


Figure 6: Dbh distribution of coarse woody debris (natural mortality) in plots 1-3 (from left to right). Standing CWD is defined a stump if is less than 130 cm high, and a snag otherwise. Solid lines represent ratio of dead to live trees for each size class (scale on secondary y-axis). DBH class in cm.

5. Discussion

Data from Second National Swiss Forest Inventory (WSL 2005) report, for pure Scots pine plots (more than 70% of total basal area) in the Alpine region, a SDI_{max} of 1348, as represented by the 98th percentile of the SDI distribution. The absolute maximum is 1620. Del Río et al. (2001) obtained a SDI_{max} of 1444, although they applied a different self-thinning slope. Other referenced maximum SDI for Scots pine in Europe range from 1229 (Sterba 1981) to 1368 (Palahí et al. 2002). Even though the datasets used in their studies show differences of origin (planted or naturally regenerated stands), treatment (untreated or lightly thinned), stocking (different initial spacing), and plot selection criteria (which are explicit only in one study), the SDI_{max} seems fairly constant. We also compared the sample maximum against SDI obtained by available yield tables for Scots pine in Europe (Weidemann 1949; Décourt 1965; Hamilton and Christie 1971; Marschall 1976; Thren 1987; Jansen et al. 1996), computed from quadratic mean dbh and density of principal yield and removals predicted for the highest site index in each table. The estimate from the current study was 12 to 36% higher than SDI from yield tables; this can be explained assuming that the removals planned by the yield tables had a stronger effect than natural mortality in shaping future density and crowding of the stand.

We could not find any significant difference in the self-thinning slope from Reineke's suggested value of -1.6. The constancy of the self-thinning process in Scots pine was noted by Włoczewski (1968), who pointed out that the "percent elimination of trees" in given time intervals was comparable among different habitats, even if the absolute densities were not similar. According to Reineke (1933), maximum density lines of different species differ only for the intercept value; within a species, different ecotypes or site fertility levels determine a higher or lower speed of advancement along the same self-thinning trajectory. Several sources, however, suggested that maximum potential density is to be understood as a site property (Assmann 1970; Sterba 1987). Different site qualities, therefore, have often been characterized by different SDI_{max}, by varying either the intercept or the slope of the self-thinning line (Sterba 1981; Hynynen 1993; Morris 2002; Monserud et al. 2004). A one-way ANOVA showed significant differences in mean SDI values when they were grouped by forest type (I.P.L.A. 2003a); the Mid-continental type Scots pine plots had the higher SDI on average, followed by the Inner-alpine, the Interior Hills and the Heath forest types ($p < 0.05$). We could not draw definitive conclusions, since sample size was very small (3 to 63 data per forest type) and a comparison between the maximum SDI values rather than the mean is advisable. Therefore, we defined a single SDI_{max} value for all the plots, holding both the slope and the intercept of the self-thinning line constant.

Relative density in most Scots pine stands (75%) is less than 0.6, the lower threshold of the self-thinning zone or "zone of imminent competition mortality" (Drew and Flewelling 1979). Land use changes played a major role; many stands established on recently abandoned areas, and even on the best sites, have not undergone self-thinning yet, but may soon be expected to do so. A relative density corresponding to 25% of SDI_{max} has generally been associated with the transition from open-grown to competing populations (Long 1985). We suggest that an SDI of 350 be used to represent the onset of competition; this level has already been reached in the majority of stands.

A distinct developmental pattern characterizes the sample plots analyzed in this study, which in our hypothesis does not differ for site fertility. The youngest stand was established 30 years ago on a former alpine meadow. Remains of irrigation channels and stone walls can still be seen in the stand, evidence of the previous agricultural use of this land. Its relative density is 0.61, suggesting that this stand has just entered the phase of active self-thinning and mortality due to intraspecific competition. This is consistent with Suchecki's (1947) predictions, according to which self-thinning induced mortality in Scots pine stands of central Europe may begin at an age of 30-40 years (even sooner on poorer sites, i.e., at the age of 10-20 years) and usually peaks at 40-50 years.

The origin of the second stand is unclear, but field evidence suggests that its origin could be similar to the younger stand, i.e., initial encroachment on grassland, with fire possibly playing a role in stand initiation. Resin collection scars suggest that the main cohort could be between 90 and 130 years old. This stand, which is located on the slope opposite the first one, represents the next developmental stage, with increased tree size and decreased density due to self-thinning. Relative density is 0.95, meaning a longer and more intense influence of competition mortality on the stand. Still, there is some growing space available not to Scots pine but to more tolerant species such as beech (*Fagus sylvatica* L.), Norway spruce and silver fir (*Abies alba* Mill.), that are beginning to establish as a shaded regeneration layer under the pine overstory and may represent the future successional development of the stand.

The stand probably represents an old protection forest which was preserved from felling during the past centuries. A gap-opening phase can be distinguished, characterized by a much lower absolute and relative densities (0.49), which are below the self-thinning threshold. Natural mortality of older trees and the impact of occasional felling during the last 20 years made some growing space available for a new cohort, which is establishing in dense groups in the gaps and gives the stand a distinct two-storied structure. It is unclear whether the stand has already gone through a self-thinning phase, the intensity of competition being later attenuated by tree removal, or rather the initial density was too low to trigger density-dependent mortality. The distance of this stand from the self-thinning boundary may reflect Zeide's (1995) hypothesis that mortality of old trees exceeds lateral growth of crowns in overmature stands. This process results in a progressive accumulation of gaps as the stand gets older, so that the stand development trajectory drops below the maximum density line. The extent of the "mature stand boundary", as defined by Shaw and Long (in review), could not be quantified because of the limited number of mature, fully-stocked plots in our sample.

SDI values referred to in this discussion were calculated using Reineke's traditional method, that is based upon the assumption that every tree in a stand has the same dbh (i.e., the QMD of the stand), and therefore does not reflect the actual dbh distribution of the stand. When the summation method is used, each tree's contribution to overall stocking is taken into consideration, resulting in a generally lower SDI (Shaw 2000). The ratio between SDI and SDI_{sum} has been found to be inversely related to uneven-agedness of the stand, as measured by the skewness of the dbh distribution of the stand (Ducey and Larson 2003; Long and Shaw 2005; Vacchiano et al. 2005). Since Scots pine tends to assume a fairly even-aged structure, the ratio SDI_{sum} /SDI is rather constant between the plots (0.96 in permanent plots 1 and 2, 0.87 in plot 3). Therefore, for management purposes, relative density estimates can be considered roughly equivalent whether they are obtained with the traditional or the summation method.

Size distribution analysis provided more detail about the processes that underlie competitive interactions. Any resource-mediated competitive interaction among individual plants can be placed somewhere along a continuum between completely size symmetric competition, where resource uptake among competitors is independent of their relative sizes, and completely size-asymmetric competition, where the largest plants obtain all the contested resources (Schwinning and Weiner 1998).

Size inequality in a population is considered the outcome of asymmetric competition only (Hara 1988; Yastrebov 1996). A certain degree of initial size heterogeneity may appear because of genetic heterogeneity (Bonan 1988), microsite or spatial heterogeneity (Weiner 1985), and seed heterogeneity (Westoby and Howell 1986). The marked unimodal distribution of the younger stand and the modality of its establishment suggest that encroachment process was quite fast (Rouvinen and Kuuluvainen 2005), so that the new stand had a fairly homogeneous size distribution. After crown closure, an increasing competition for light may have favored the bigger individuals, which grow disproportionately more than smaller ones (Wilson 1988), thus increasing size differentiation up to the value observed in the first plot (Gini = 0.20). With the onset of self-thinning, the smallest individuals are outcompeted and die, leading to a more homogeneous size distribution shifted to an higher dbh (Gini = 0.14 in the second stand). The establishment of a new cohort later on resulted in a marked size heterogeneity (Gini = 0.44 in the oldest plot).

This trend is confirmed by coarse woody debris size distributions; in the two self-thinning stands mortality is concentrated in the smallest (suppressed) size classes. The highest mortality frequencies are associated with small or middle-sized trees, according to how long self-thinning has been going on in the stands (many small trees in plot 1, fewer but bigger trees in plot 2). No evidence of self-thinning processes could be drawn from CWD size distribution in plot 3, where mortality occurs in all size classes and where the removal of bigger trees is responsible for the newly created gaps.

6. Conclusion

SDI provides insight into structural dynamics in Scots pine stands; data from a regional forest inventory have been used to characterize relative density and self-thinning in intensively measured permanent plots. Integration of independent analysis methods, field evidence and historical information helped describing the role and intensity of competition in the studied stands, at the same time providing a basis for the understanding of the past and future development of Scots pine populations.

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