A density management diagram for Norway spruce in the temperate European montane region

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Corresponding Author	Family Name	**Vacchiano**
	Particle	
	Given Name	**Giorgio**
	Suffix	
	Division	Department of AGROSELVITER
	Organization	University of Torino
	Address	Via L. da Vinci 44, 10095, Grugliasco, TO, Italy
	Email	gvacchiano@gmail.com
Author	Family Name	**Derose**
	Particle	
	Given Name	**R. Justin**
	Suffix	
	Division	
	Organization	Rocky Mountain Research Station, Forest Inventory and Analysis
	Address	507 25th Street, 84401, Ogden, UT, USA
	Email	
Author	Family Name	**Shaw**
	Particle	
	Given Name	**John D.**
	Suffix	
	Division	
	Organization	Rocky Mountain Research Station, Forest Inventory and Analysis
	Address	507 25th Street, 84401, Ogden, UT, USA
	Email	
Author	Family Name	**Svoboda**
	Particle	
	Given Name	**Miroslav**
	Suffix	
	Division	Department of Silviculture, Faculty of Forestry and Wood Sciences
	Organization	Czech University of Life Sciences
	Address	Kamycka 129, 16521, Praha 6 Suchdol, Czech Republic
	Email	
Author	Family Name	**Motta**
	Particle	
	Given Name	**Renzo**
	Suffix	

	Division	Department of AGROSELVITER
	Organization	University of Torino
	Address	Via L. da Vinci 44, 10095, Grugliasco, TO, Italy
	Email	

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Abstract	Norway spruce is one of the most important conifer tree species in Europe, paramount for timber provision, habitat, recreation and protection of mountain roads and settlements from natural hazards. Although natural Norway spruce forests can exhibit diverse structures, even-aged stands can arise after disturbance and are the result of common silvicultural practice, including off-site afforestation. Many even-aged Norway spruce forests are actively managed, facing issues such as senescence, insufficient regeneration, mechanical stability (stem form), sensitivity to biotic disturbances, and restoration. We propose the use of Density Management Diagrams (DMD), stand-scale graphical models originally designed to project growth and yield of even-aged forests, as a heuristic tool for assessing the structure and development of even-aged Norway spruce stands. DMDs are predicated on basic tree allometry and the assumption that self-thinning occurs predictably in forest stands. We designed a DMD for Norway spruce in temperate Europe based on wide-ranging forest inventory data. Quantitative relationships between tree- and stand-level variables that describe resistance to selected natural disturbances were superimposed on the DMD. These susceptibility zones were used to demonstrate assessment and possible management actions related to, for example, windfirmness and effectiveness of the protective function against rockfall or avalanches. The Norway spruce DMD provides forest managers and silviculturists a simple, easy-to-use, tool for evaluating stand dynamics and scheduling needed density management actions.

Keywords (separated by '-')	Decision support systems - Natural hazards - *Picea abies* (L.) Karst. - Protective function - Self-thinning - Silviculture
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ORIGINAL PAPER

A density management diagram for Norway spruce in the temperate European montane region

Giorgio Vacchiano · R. Justin Derose · John D. Shaw · Miroslav Svoboda · Renzo Motta

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Abstract Norway spruce is one of the most important conifer tree species in Europe, paramount for timber provision, habitat, recreation and protection of mountain roads and settlements from natural hazards. Although natural Norway spruce forests can exhibit diverse structures, even-aged stands can arise after disturbance and are the result of common silvicultural practice, including off-site afforestation. Many even-aged Norway spruce forests are actively managed, facing issues such as senescence, insufficient regeneration, mechanical stability (stem form), sensitivity to biotic disturbances, and restoration. We propose the use of Density Management Diagrams (DMD), stand-scale graphical models originally designed to project growth and yield of even-aged forests, as a heuristic tool for assessing the structure and development of even-aged Norway spruce stands. DMDs are predicated on basic tree allometry and the assumption that self-thinning occurs predictably in forest stands. We designed a DMD for Norway spruce in temperate Europe based on wide-ranging forest inventory data. Quantitative relationships between tree- and stand-level variables that describe resistance to selected natural disturbances were superimposed on the DMD. These susceptibility zones were used to demonstrate assessment and possible management actions related to, for example, windfirmness and effectiveness of the protective function against rockfall or avalanches. The Norway spruce DMD provides forest managers and silviculturists a simple, easy-to-use, tool for evaluating stand dynamics and scheduling needed density management actions.

Keywords Decision support systems · Natural hazards · *Picea abies* (L.) Karst. · Protective function · Self-thinning · Silviculture

Introduction

Norway spruce (*Picea abies* (L.) Karst.) is one of the most important tree species in the mountain ranges of central and southern Europe. Norway spruce stands are important for timber production and provide important ecosystem services (Pretzsch et al. 2008). In mountain regions, these forests can provide protection from natural hazards such as avalanches, rockfall, or landslides (Bebi et al. 2001; Mayer and Ott 1991). Norway spruce forests also provide habitat for game, and may harbor endangered fauna or flora (e.g., Nascimbene et al. 2009).

Vast areas of pure, monolayered Norway spruce plantations are common in many European montane and lowland landscapes, oftentimes usurping the space of natural forests (Hansen and Spiecker 2004). The species has been introduced far outside its natural range, both in countries where it occurs naturally, for example, in Germany and Norway, and in novel areas such as Denmark, Belgium, and Ireland (Skroppa 2003). Natural and semi-natural Norway spruce forests, on the other hand, are relatively

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G. Vacchiano (✉) · R. Motta
Department of AGROSELVITER, University of Torino, Via L. da Vinci 44, 10095 Grugliasco, TO, Italy
e-mail: gvacchiano@gmail.com

R. J. Derose · J. D. Shaw
Rocky Mountain Research Station, Forest Inventory and Analysis, 507 25th Street, Ogden, UT 84401, USA

M. Svoboda
Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Kamycka 129, Praha 6 Suchdol 16521, Czech Republic

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rare (Parviainen et al. 2000; Motta 2002) and often exhibit multiple structural and compositional attributes depending in part on the disturbance regime (Shohorova et al. 2009). These structures range from sparse, multilayered subalpine stands (Kulakowski et al. 2004; Krumm et al. 2011) to monolayered forests resulting from severe disturbances (Fisher et al. 2002; Angelstam and Kuuluvainen 2004), to uneven-aged mixtures (Svoboda et al. 2010, 2012).

Windstorms, snow loading, and insects are among the most damaging disturbance agents in Norway spruce stands (Klopcic et al. 2009; Svoboda et al. 2012). Increasing susceptibility to natural disturbances (Schlyter et al. 2006; Seidl et al. 2011), in combination with aging stands and increasing demand for enhanced structural complexity and close-to-nature forest structures (Gamborg and Larsen 2003), results in a silvicultural conundrum that cannot be adequately addressed using simple management tools (e.g., yield tables). Given the importance of Norway spruce in managed montane forests of central-southern Europe, it is important to develop ecologically based decision support systems that allow for the development of realistic management scenarios and enable the comparison of alternative schedules with respect to the evaluation criteria of interest (e.g., volume production, carbon storage, stand stability, structural diversity, nature conservation, and biodiversity).

Density management diagrams (DMD) are empirical models of even-aged stand dynamics (Jack and Long 1996). They reflect fundamental relationships involving tree size, stand density, site occupancy, and self-thinning. Allometric relationships between mean tree size, age, height, and yield are portrayed allowing users to design treatments by plotting both current and desired future stand structure on the DMD. Alternative management strategies that accomplish diverse objectives can be simultaneously compared and their efficacy evaluated at a glance. In this paper, we analyzed data from Norway spruce stands to construct a DMD with wide applicability across montane regions of central-southern Europe. Using specific examples of (1) maximizing volume production, (2) mechanical stability against wind damage, (3) avalanche protective function, and (4) potential resistance to spruce bark beetle (*Ips typographus* L.), we demonstrate the usefulness of the Norway spruce DMD.

Methods

Data sources

The data used to develop the Norway spruce DMD came from multiple sources (Table 1) that covered many regions of central-southern Europe (Fig. 1) and included 5,656 plots. Most areas occupied by temperate European montane forest were represented in the data set. We excluded areas with few pure Norway spruce forests (e.g., Balkans) or countries where forest inventory data were not readily accessible.

1. Data from France were obtained from the French National Forest Inventory (http://www/.ifn.fr/spip/) for the inventory period 2005–2009. The French inventory design implemented three nested fixed-area plots [6, 9, and 15 m radius for trees ~7–22.5 cm, 22.6–37.5 cm, and 37.5+ cm in diameter at breast height (DBH), respectively] from which trees per hectare (N) expansion factors were calculated. The French Inventory also included tree height (H) and estimated tree volume (Vidal et al. 2007).
2. Data from the Czech Republic came from two regions, Sumava and Tajga. In the Sumava region, the inventory design was three nested fixed-area plots (3.5, 7, and 12.6 m radius for trees 7–14.9 cm, 15–29.9, and 30+ cm DBH, respectively) and did not include estimates of tree volumes (Čížková et al. 2011). In the Tajga region, the inventory consisted of one 12.5-m-radius fixed-area plot where DBH and H were measured and estimates of volume included for all trees >10 cm.
3. Data from Romania came from the mountain regions of Călimani and Giumalau (Cenuşă 1992). The inventory in these regions used either a 500- or 1,000-m^2 fixed-area plot with a lower DBH cutoff of 10 cm. Individual-tree heights for all trees were estimated using locally calibrated models and there were no estimates of volume (M. Svoboda—unpublished data).
4. Italian data came from multiple regions and inventory designs. At Aosta and Piemonte (IPLA 2003) fixed-area plots ranged from 8 to 15 m radius depending on overstory density and the lower DBH cutoff was ~7 cm; species-and site-specific volume equations were provided. At Paneveggio and San Martino (Berretti and Motta 2005) fixed-area plots of 12 m radius with a lower DBH cutoff of 17 cm were used and no estimates of volume were made. At Val Pontebbana (Castagneri et al. 2010) 12-m-radius fixed-area plots were sampled with a lower DBH cutoff of ~7 cm. In Valbona, 400-m^2 fixed-area plots were used with a lower DBH cutoff of ~7 cm (Motta et al. 2006). At Burgusio, Lasa, Latemar, Luttago, Meltina, Naturno, Valle Aurina, and for plots of the National Forest Inventory (INFC 2006), variable radius plots (basal area factor = 4 m^2 ha^{-1}) were employed with a lower DBH cutoff of ~4 cm and volume was not estimated.

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Table 1 Source of data for the Norway spruce DMD and estimates of SDI_{max} by location (SDI_p for pure, even-aged Norway spruce stands)

ID	Dataset name (region)	Country	No. of plots	DBH cutoff (cm)	Plot size (m^2)	98th percentile SDI_{max}
1	Aosta	Italy	156	7	201–707	1,209
2	Piemonte	Italy	65	7	201–707	1,701
3	National forest inventory	Italy	401	4	Relascopic	1,571
4	Burgusio	Italy	91	4	Relascopic	1,080
5	Lasa	Italy	251	4	Relascopic	1,473
6	Latemar	Italy	322	4	Relascopic	1,745
7	Luttago	Italy	72	4	Relascopic	1,007
8	Meltina	Italy	256	4	Relascopic	1,383
9	Naturno	Italy	304	4	Relascopic	1,220
10	Valle Aurina	Italy	155	4	Relascopic	1,493
11	Paneveggio	Italy	91	17	452	1,321
12	San Martino	Italy	91	17	452	1,278
13	Valbona	Italy	66	7	400	1,592
14	Val Pontebbana	Italy	33	7	452	1,162
15	Tajga	Czech Republic	78	7	491	755
16	Sumava Certovo	Czech Republic	66	7	38–499	1,278
17	Sumava NP	Czech Republic	38	7	38–499	1,221
18	Sumava large plots	Czech Republic	15	7	1,000–2,500	1,121
19	Sumava Trojmezna	Czech Republic	18	7	38–499	826
20	Călimani	Romania	40	10	500–1,000	1,425
21	Giumalau	Romania	41	10	500–1,000	1,270
22	Baden-Wurttnenberg	Germany	399	7	Relascopic	1,464
23	France 2005	France	522	7	113–707	1,206
24	France 2006	France	526	7	113–707	1,277
25	France 2007	France	558	7	113–707	1,305
26	France 2008	France	489	7	113–707	1,086
27	France 2009	France	471	7	113–707	1,238
28	Parangalitsa	Bulgaria	227	4	100	2,653

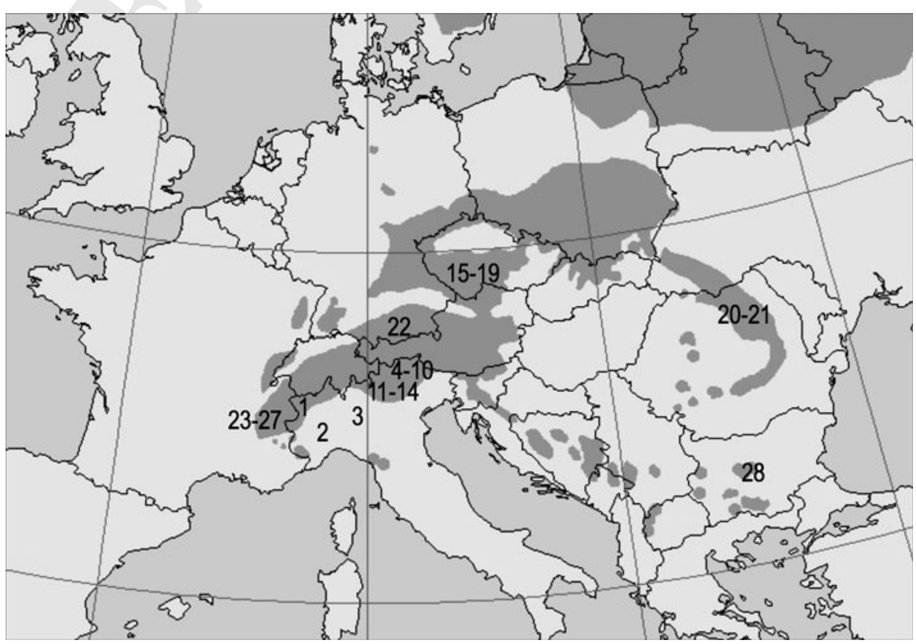

Fig. 1 Distribution of Norway spruce in central-southern Europe (after Schmidt-Vogt 1977) and location code for data used for DMD construction. Refer to Table 1 for location names

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5. Bulgarian data referred to remote-sensed, internally homogenous forest patches in the Parangalitsa Reserve, including a number of post-disturbance stands (Panayotov et al. 2011). A total of 227 100-m^2 plots were sampled with a lower DBH cutoff of 4 cm and no information on *H* and volume.
6. German data came from the Second National Forest Inventory of Germany (Schmidt and Kandler 2009). Trees with a minimum DBH of 7 cm were selected using the angle-count method (horizontal point sampling) with a basal area factor of 4 m^2 ha^{-1}. The attributes recorded included species, DBH, tree age, and *H*.

Size–density relationships

Using the tree-level data, we calculated *N*, quadratic mean diameter (QMD), basal area, percent basal area of Norway spruce, stand density index (SDI), and stand top height (HT_{100}), defined as the average height of the 100 largest (DBH) trees per hectare. SDI was calculated two ways: (1) Reineke (SDI_p: Reineke 1933, modified by Long and Daniel 1990),

$$SDI_p = N(QMD/25.4)^{1.605}, \quad (1)$$

and (2) summing the SDI of each *i* th tree in a stand (SDI_{sum}: Shaw 2000),

$$SDI_{sum} = \Sigma_N \left[N_i (DBH_i/25.4)^{1.605} \right] \quad (2)$$

so that stands with simple structure could be filtered from the data using the SDI_{sum}:SDI_p ratio (SDI_{ratio}). SDI_{ratio} has been shown to theoretically differentiate even-aged stands, which have strong unimodal diameter distributions ($SDI_{ratio} \geq 0.9$), from uneven-or multi-aged stands, which show increasing skewness in their diameter distribution ($SDI_{ratio} < 0.9$) (Ducey 2009). SDI_{ratio} has been used to indicate relatively even-aged stands for building DMDs (Long and Shaw 2005, Shaw and Long 2007). Before estimating the self-thinning boundary, the plot-level data were filtered for Norway spruce composition ≥80 % (determined by percent basal area) and for even-aged stands ($SDI_{ratio} \geq 0.9$), which resulted in 1,609 plots.

We paid particular attention to determining the maximum size–density line. In order to filter for fully stocked stands, we used a binning method (Bi and Turvey 1997) (200 N bins) from which maximum observations of SDI_{sum} were extracted before the maximum self-thinning line was fit by ordinary least-squares (OLS) regression. We assessed whether a lower DBH cutoff of 4, 7, 10, or 17 cm had any effect on SDI_{max} (Curtis 2010) and/or the slope determined during the binning method by refitting the OLS for each DBH cutoff group. Moreover, since differing self-thinning slopes are reported in the literature, both between- and within-tree species (including Norway spruce: Sterba 1987; Hynynen 1993; Monserud et al. 2005; Pretzsch and Biber 2005; Pretzsch 2006; Schütz and Zingg 2010; Charru et al. 2011), we tested whether Reineke's (1933) suggested slope of −1.605 was statistically different from that of our linear fit. Subsequently, we shifted the OLS line to cross the point of maximum stocking. SDI_{max} indicates maximum growing space occupancy (Yoda et al. 1963), so that plots falling above the line should be exceedingly rare. Therefore, we assumed the 98th percentile of the SDI_{sum} frequency distribution appropriately characterized the maximum attainable SDI. Finally, we juxtaposed lines on the DMD to describe relative stand density (percent of SDI_{max}) following the recommendations of Long (1985). That is, 25 % of SDI_{max} represents crown closure, 35 % of SDI_{max} indicates the beginning of individual-tree growth reduction due to inter-tree competition, and at 60 % of SDI_{max}, the onset of severe competition.

We tested for the existence of a Mature Stand Boundary (MSB) in the maximum self-thinning limit (Shaw and Long 2007) by fitting the following three-parameter function:

$$QMD = a(N_{max} + b)^c, \quad (3)$$

where N_{max} are observations of maximum *N* for each 0.01 class of Log_{10} QMD. Only plots where QMD ≥ 15 cm were used, because stands in the smaller size classes are not needed to establish the MSB. Subsequently, we shifted the curve developed in Eq. 3 such that the maximum SDI value on the curve was asymptotic to the SDI_{max} on the DMD.

Top height and volume

When included on a DMD, HT_{100} can be used with local site index curves to assess and quantify the temporal development of a particular stand (Jack and Long 1996). Using plot data that included observations of HT_{100}, we modeled QMD as a function of HT_{100}, attenuated by an inverse logarithmic function of tree density:

$$QMD = HT_{100}(b_1 - b_2 \ln N) \quad (4)$$

To generate stand-level volume (VOL) isolines on the DMD, we modeled VOL as a power function of QMD and *N* (Eq. 5a), then rewrote the equation as QMD = *f*(VOL), where VOL is total standing volume (m^3 ha^{-1}) for plot data with volume observations:

$$VOL = c_1 + c_2 N\, QMD^{c_3} \quad (5a)$$

$$QMD = \left[(c_1 + c_2 N)^{-1} VOL \right]^{(1/c_3)} \quad (5b)$$

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We plotted HT_{100} and VOL isolines on the DMD for ranges of 20–50 m, and 200–1,200 m^3 ha^{-1}, respectively. Different inventories may have used different equations for tree or stand volume, generating idiosyncrasies when pooling all volume data in one model. However, because we were missing inventory-specific volume equations, we used original data as much as possible, acknowledging that DMD isolines merely represent average conditions across the entire dataset.

All models were assessed for parameter significance and goodness-of-fit by computing adjusted R^2 and root mean square error (RMSE). We determined that both models had little or no bias by inspecting residual plots over the predictor variables, elevation when available, SDI, basal area, region, and whether the plot had a lower DBH cutoff of 4, 7, 10, or 17 cm.

Disturbances and site index

To illustrate the advantages of the DMD in designing silvicultural strategies to maximize resistance to disturbances and protection from natural hazards, we superimposed “susceptibility zones” on the diagram, which encapsulate combinations of size and density that (a) fulfill an effective protection against avalanche release; and (b) result in a low risk of wind damage. Thresholds for (a) were summarized as follows (after Berretti et al. 2006; Gauquelin and Courbaud 2006):

(a) Basal area $\geq$ 25 m^2 ha^{-1} when QMD = 25 cm, and $\geq$7.5 m^2 ha^{-1} when QMD = 10 cm for effective snowpack stabilization if slope is steeper than 35°;
(b) Live crown ratio $\geq$60 % in trees or cluster of trees supporting the stability of the stand. We relaxed this requirement to $\geq$33 %, representing a minimal acceptable level of individual-tree vigor that should be ensured with a relative SDI < 0.60 (Long 1985);
(c) H/DBH ratio <80 in dominant trees. H/DBH (mean or dominant) ratio cannot be read directly off the DMD. However, assuming that DBH is normally distributed in a stand and that dominant diameter (DD) is equivalent to the 90th percentile of such distribution (Z value = +1.64), DD can be computed by

$$DD = 1.64\sigma_{DBH} + QMD, \qquad (6a)$$

where σ_{DBH} is the standard deviation of the DBH distribution in the stand. In order to represent risk zones on the DMD, we assumed that $\sigma_{DBH} = 0.3$ QMD and solved Eq. 6a for QMD:

$$QMD = 0.67\ DD, \qquad (6b)$$

to be substituted in HT_{100}/QMD ratio from Eq. 4 and constrained to $\leq$0.8. This allowed the influence of smaller, suppressed trees to be removed so that only the slenderness of dominant trees was considered (Castedo-Dorado et al. 2009);
(d) Gap size $\leq$1.5 times tree height (in order to avoid tree-free patches prone to dangerous snow gliding). If square spacing is assumed, a Mean nearest neighbor distance (m) (MNND) can be computed as the square root of the reciprocal of N. We introduced a multiplier to account for clumped patterns, that is, the ratio between maximum and observed nearest neighbor index (NNI). NNI ranges from 0, when trees are highly clumped, to 2.1491, when trees are arranged along a hexagonal grid (Clark and Evans 1954):

$$MNND = \left(2.1491\ NNI^{-1}\right) \times 100\, N^{-0.5}, \qquad (7)$$

subsequently constrained to $\leq 1.5HT_{100}$ and used to back calculate critical N–HT_{100} combinations.

While the DMD can be used to assess avalanche hazard related to stand structure, other predisposing conditions (e.g., weather, topography, characteristics of snowpack, and terrain ruggedness) must be evaluated independently.

Thresholds for live crown ratio followed those by Riou-Nivert (2001), who established low, medium, and high wind risk zones for conifer species, based on the relationship between QMD and HT_{100} (Fig. 2). Mitchell (2000) suggested that such general zones of stability exist for uniform stands of temperate zone conifers.

An appropriate site index (SI) curve allows the estimates of HT_{100} on the DMD to be a surrogate for time (Drew and Flewelling 1979). SI estimates were not included in the raw data. In order to provide SI curves applicable to even-aged, pure Norway spruce stands across temperate Europe, we fitted a modified Richards' model of height growth (Sterba 1976) to yield tables from Eisacktal, South Tyrol (Moser 1991), which exhibited a wide range of fertility classes (i.e., HT_{100}: 7.9–45.8 m at age 100). All statistics were performed in the R environment version 2.14.1 (R Development Core Team 2011).

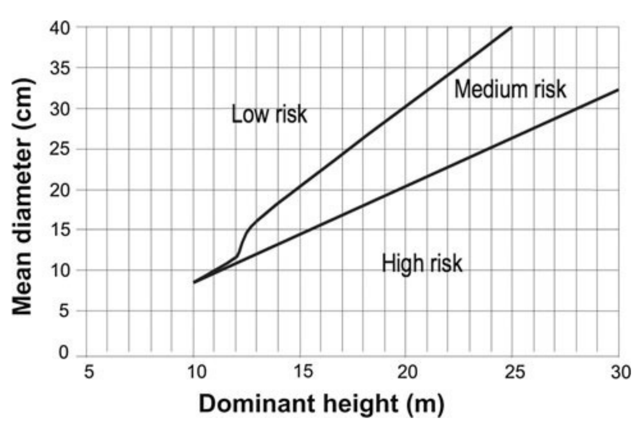

Fig. 2 Wind stability zones for even-aged coniferous stands based upon HT_{100} and QMD (after Riou-Nivert Riou–Nivert 2001

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Results

Twenty-nine percent of the original Norway spruce data set, that is, 1,609 of 5,656 inventory plots (Table 2) were used to fit a maximum size–density relationship characterizing montane Norway spruce in central-southern Europe. Slope of the self-thinning line was −1.497 (adjusted $R^2 = 0.94$); the 95 % confidence interval of the slope coefficient from OLS regression (−1.671 to −1.324) included Reineke's value of −1.605. SDI_{max} was 1,461 (Fig. 3); coefficient of variation between the 28 regions was 26 %, mean = 1334.28, and SD = 345.39 (Table 1). Binning by different DBH cutoff values did not change our results with respect to the significance of −1.605, except for the 17 cm cutoff that produced a non-significant regression slope likely due to limited sample size (Table 3). However, the lowest DBH cutoff (4 cm) produced the highest SDI_{max}. Parameters of the MSB (Eq. 3) were $a = 3330.105$, $b = 185.158$, and $c = -0.0656$ (adjusted $R^2 = 0.96$).

Top height and volume equations were statistically significant (Table 4). Some bias was revealed in residual plots over observed volume (Fig. 4); however, these occurred in poorly stocked stands (i.e., <50 $m^3\ ha^{-1}$) and do not constitute a concern for using the DMD in practice. The QMD-HT_{100} model exhibited some high regional bias (Table 5); a 95 % confidence envelope about the mean of QMD residuals included zero in 7 out of 14 sites for the HT_{100} model (Eq. 4), and 8 out of 10 sites for the VOL model (Eq. 5b).

Discussion

DMD characteristics

DMDs that cover widely distributed species (e.g., Long and Shaw 2005) are indicative of average growth patterns and allometric relationships of monospecific stands. We assumed that allometric equations, when portrayed on the DMD, were invariant across all sites (Weiner 2004). Conditions under which the self-thinning boundary may shift include, at the local scale, genetic differences (Buford and Burkhardt 1987), and severe resource deficiencies, e.g., in tree line environments (Körner 2003). However, despite deviations at certain localities (Table 5), our allometric models should be robust, in that the high number of plots used for calibration should average out local peculiarities.

Previous research has observed disparities in mortality rates of Norway spruce stands located on different elevations and aspects (Krumm et al. 2012). However, we consider these to be an effect of the different rates at which stands may progress along their trajectories of development in size–density space, while following the same overarching, species-specific, self-thinning boundary. Differences in topography, temperature, light, and soil fertility affect growth rates and, in turn, the rate of mortality during the stem-exclusion phase (Aulitzky 1984; Schönenberger 2001). In other words, a Norway spruce stand on a high-quality site will reach the boundary more quickly than the same density of trees on a lower-quality site, even though both eventually achieve the same boundary (Jack and Long 1996). This constancy is fundamental to the general utility of DMD and allows the use of site index curves to determine the time required to attain particular stand structural characteristics. Our aim was to characterize Norway spruce stands across the montane forest region in central-southern Europe using a single tool. Therefore, when using the DMD to portray stands at a specific location, managers should choose the appropriate dominant height curve, in order to account for differences in local productivity.

Maximum SDI for Norway spruce in montane forests of central-southern Europe was 1,461, which was intermediate in the range of previous regional estimates (Pretzsch 2005—Germany: $SDI_{max} = 1{,}609$; Monserud et al. 2005—Austria: $SDI_{max} = 1{,}571$; Sterba 1981—Austria: $SDI_{max} = 1{,}547$; Castagneri et al. 2008—NE Italy: $SDI_{max} = 1{,}380$), independent of the DBH measurement cutoff. Consistent with previous studies (Shaw and Long 2007), we detected a convex pattern to the self-thinning limit at high tree size–low density combinations, that is, a mature stand boundary (MSB). The most commonly suggested explanation for this process is so-called "self-tolerance" (Zeide 1985), by which growing space resulting from the death of very large trees can not be promptly reclaimed by con-specific neighboring trees, lowering the limit of possible size–density combinations. Maintaining stand size–density below the MSB is crucial for management as combinations above the line are ecologically improbable (DeRose et al. 2008).

Table 2 Summary statistics for pure, even-aged Norway spruce stands ($SDI_{ratio} \geq 0.9$, percent Norway spruce on total basal area ≥0.8)

Variable	Unit	*n*	Min	Max	Mean	SE
N	trees ha^{-1}	1,609	14	5,058	564.1	13.03
QMD	cm	1,609	7.8	115.0	34.8	0.31
HT_{100}	m	876	4.2	46.0	24.1	0.23
VOL	$m^3\ ha^{-1}$	505	0.8	1163.6	316.4	9.69
BA	$m^2\ ha^{-1}$	1,609	0.4	130.0	40.3	0.50
PRCPA	%	1,609	0.8	1.0	1.0	0.002
SDI_{sum}	–	1,609	14	2,057	705.0	8.45
SDI_{ratio}	–	1,609	0.9	1.0	1.0	0.001
Age	Years	669	8.0	338.0	108.5	2.40
Elevation	m. a.s.l.	748	82	2,230	1240.6	16.26

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Fig. 3 Selected Norway spruce stands in size–density space, SDI lines, and mature stand boundary

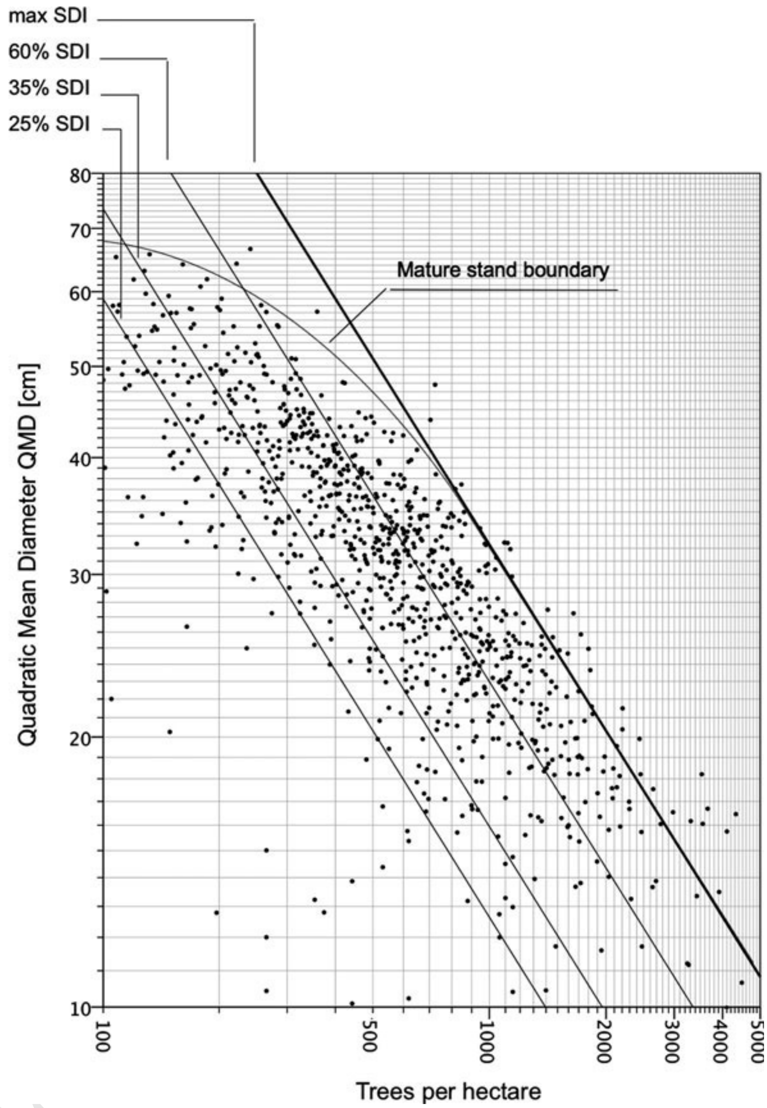

Table 3 Fit statistics of the self-thinning line computed using different DBH cutoff values

DBH cutoff (in.)	SDI_{max}	Slope	95 % min	95 % max	p	Adjusted R^2	No. of plots
0	1,461	−1.50	−1.67	−1.32	0.00	0.94	1,609
4	1,587	−1.61	−1.85	−1.36	0.00	0.90	633
7.5	1,287	−1.53	−1.95	−1.10	0.00	0.82	635
10	1,447	−1.52	−1.83	−1.20	0.00	0.91	250
17	1,355	−1.87	−3.77	0.04	0.053	0.56	91

Application of the DMD

The DMD is depicted in log(QMD)-log(Density) space with a superimposed self-thinning line and HT_{100} and VOL isolines (Fig. 5). Application of the DMD proceeds as follows: (1) identify starting conditions on the DMD (i.e., current stand structure); (2) identify target stand structure at end of rotation (EOR) and track the likely trajectory of unmanaged stand development (i.e., asymptotic to the self-thinning boundary); (3) ascertain the need for stand density regulation, e.g., to prevent the onset of competition-related mortality (∼60 % SDI) and represent the planned thinning entries on the DMD; (4) assess time to reach EOR by tracking the starting and ending HT_{100} on SI curves (Fig. 6).

Table 4 Model fit and parameters for Eqs. 4 and 5b (HT_{100} in m, QMD in cm, VOL in $m^3\ ha^{-1}$)

Parameter	Estimate	S.E.	95 % min	95 % max	Adjusted R^2	n
$QMD = HT_{100}(b_1 - b_2 \ln N)$						
b_1	3.148	0.056	3.038	3.259	0.663	1,491
b_2	0.297	0.009	0.278	0.315		
$VOL = c_1 + c_2 N\ QMD^{c_3}$						
c_1	−25.795	5.238	−36.087	−15.503	0.937	505
c_2	1.79×10^{-4}	1.6×10^{-5}	1.46×10^{-4}	2.11×10^{-4}		
c_3	2.432	0.025	2.383	2.480		

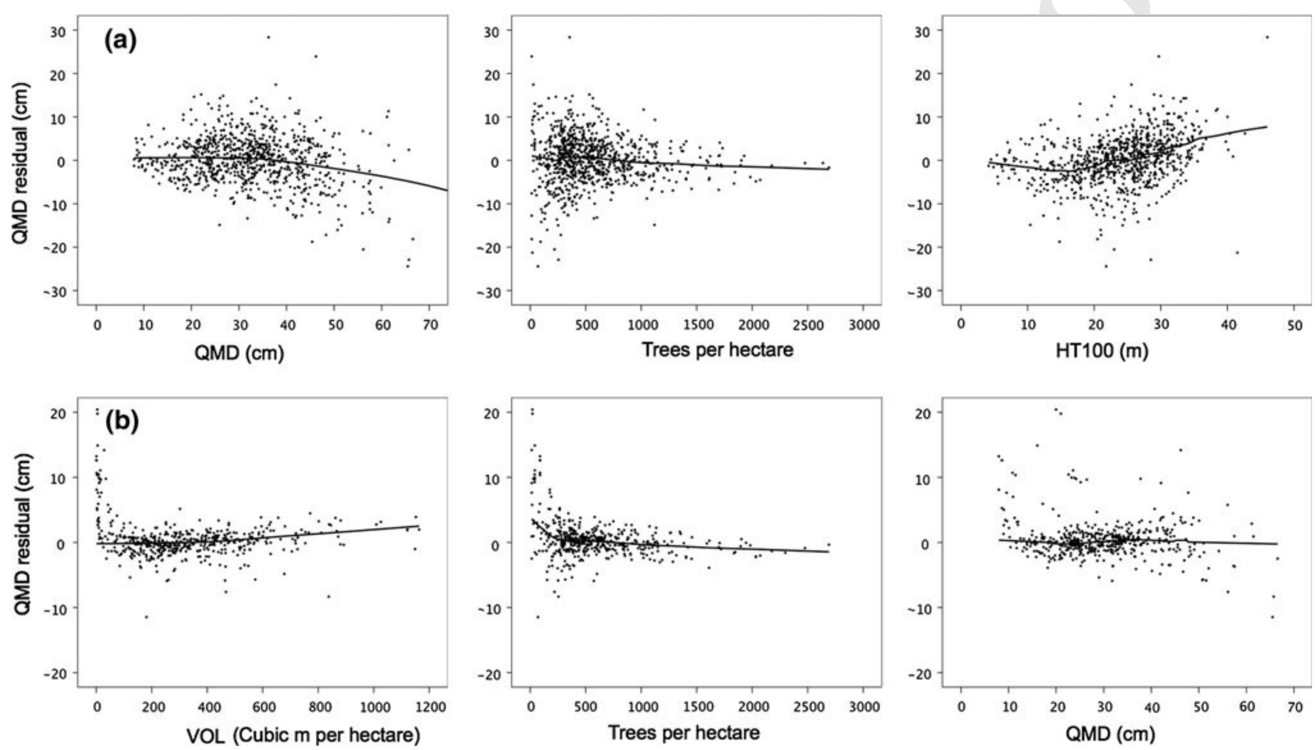

Fig. 4 Residual plots from HT_{100} (**a**) and VOL (**b**) models (Eqs. 4 and 5b). *Black lines* represent loess fit

Maximize volume production

When the goal is timber production, one can use the DMD for minimizing the time required to reach EOR at a desired mean stem diameter. In addition, by using the HT isolines in combination with site-specific potential productivity, one can incorporate future revenue and future costs into the density management regime. For example, if the desired EOR QMD was 40 cm, and the current stand has ~2,600 N (see Fig. 5), a thinning would be necessary to forestall density-dependent mortality when relative SDI approaches 60 %. This could be achieved by pre-commercially thinning the stand to ~400 N. This would drive stand development on a trajectory to meet the desired EOR of 40 cm at approximately the same time maximum stand growth is achieved (relative SDI = 60 %). Both the timing and volume of the pre-commercial thinning, or any subsequent commercial thinnings could be estimated using the HT and VOL isolines, respectively, and the return or cost associated with that treatment discounted to today's values to compare management alternatives. Similar to a volume-based regime, by using appropriate biomass conversion factors, and assuming a carbon conversion factor of 0.5, one could plan a density management regime to maximize aboveground carbon sequestration for a particular stand.

Mechanical stability against wind damage

Windstorms are the most destructive disturbance agent in temperate European forests (judged by the volume of timber damaged: Schelhaas et al. 2003), often causing extensive damage in Norway spruce, and in particular in

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Table 5 QMD mean bias (predicted–observed 95 % confidence interval) for HT_{100} and VOL models (Eqs. 4 and 5b), by location

Location	Mean bias QMD–HT_{100} (cm)		Mean bias QMD–VOL (cm)	
95 % CI	Lower	Upper	Lower	Upper
Aosta	1.31	3.17	−0.14	0.37
Piemonte	−5.49	1.88	−1.82	−0.37
Italy	−0.30	1.33	–	–
Valbona	−3.67	−1.23	−0.39	1.00
Val Pontebbana	−3.52	0.68	−0.62	1.05
Tajga	2.34	3.57	0.74	2.82
Sumava NP	−2.99	−1.10	–	–
Călimani	3.29	5.22	–	–
Giumalau	5.41	8.14	–	–
France 2005	−3.57	−0.13	−0.43	1.78
France 2006	−3.05	−0.47	−0.52	1.06
France 2007	−3.46	0.77	−0.48	2.24
France 2008	−1.22	2.80	−0.04	2.67
France 2009	−2.51	0.50	−0.76	0.89

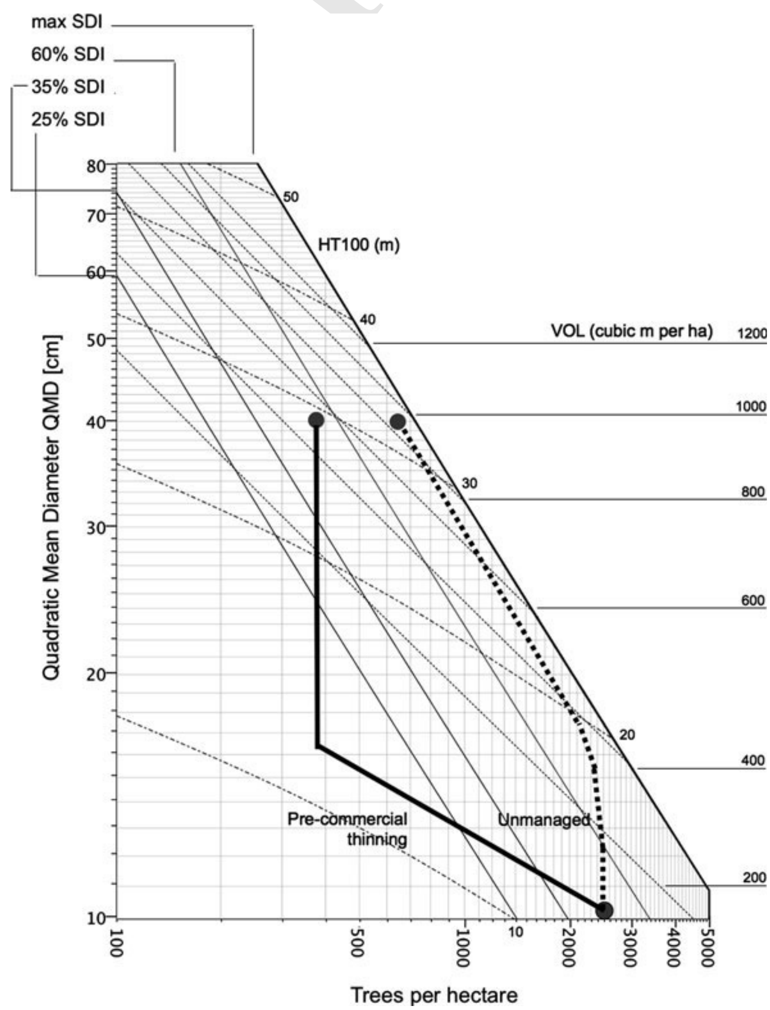

Fig. 5 DMD for Norway spruce in the central-southern European montane ecoregion, and working example of stand trajectories for unmanaged and a pre-commercial thinning alternative (starting stand conditions: $N = 2{,}500$, QMD = 10 cm; end of rotation: QMD = 40 cm). Competition-related mortality onsets at 60 % SDI and higher. Target QMD is reached in 70 years in the working example, as opposed to 90 years in the unmanaged alternative, on a medium fertility site (SI = 23.6 m, see Fig. 6)

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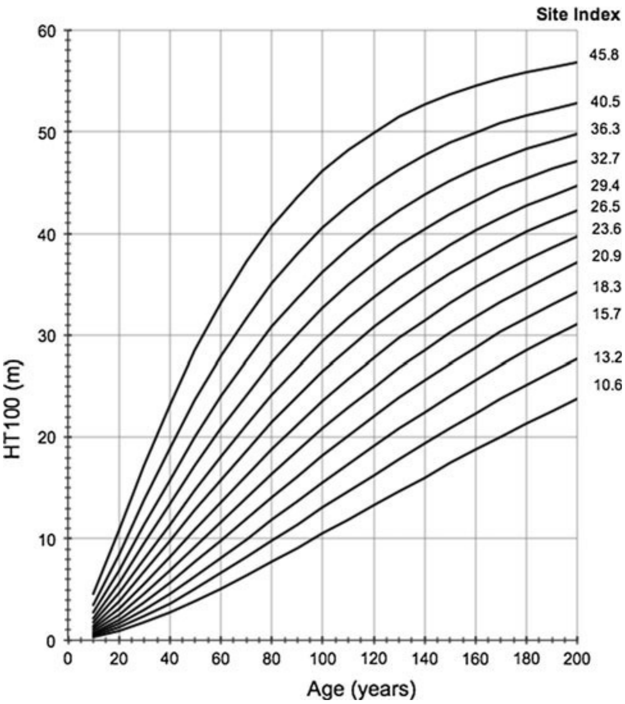

Fig. 6 Site index curves from Eisacktal (South Tyrol) yield tables

structurally homogeneous stands (Schmidt-Vogt et al. 1987). Tree damage begins at wind speeds of 15 m s^{-1} and can be catastrophic at 25 m s^{-1} (Zajaczkowski 1991). Susceptibility is higher for slender trees (e.g., Rottmann 1986; Thomasius 1988; Riou-Nivert 2001; Dobbertin 2002) and short, broad crowns (Schütz et al. 2006), a condition created through stand dynamics characterized by intense inter-tree competition. When risk zones for wind damage are superimposed on the DMD (Fig. 7), two types of management action are supported: (1) the ability to assess current conditions relative to risk, and (2) the possibility of projecting the effect of interventions which aim to maintain or drive stand structures into low-risk areas as long or quickly as possible. For example, the second management approach is depicted in the example of an unmanaged stand trajectory portrayed in Fig. 7. Among structural attributes, a threshold of ~1,800 trees ha^{-1} strongly differentiates high and medium susceptibility to wind damage. By contrast, the threshold-to-low susceptibility is mainly determined by tree slenderness, where "safe" values are typically encountered in low-density stands. From such results, we conclude that the typical even-aged Norway spruce stand (either natural or planted) is characterized by a medium risk of wind damage.

First glance at our Norway spruce stand plotted on the DMD might indicate that a heavy thinning may effectively lower stand susceptibility to wind damage, but in dense stands, it may result in sudden isolation of trees with high height-to-diameter ratio, and hence, increase the probability of damage by breakage or uprooting (Thomasius 1980).

While uneven-aged stands are acknowledged to have higher resistance to wind (e.g., Shorohova et al. 2008), they cannot be accurately represented on the diagram. Additional limitations of DMD are (a) they cannot track risk factors unrelated to stand structure, for example, soil (trees are much more vulnerable to wind damage on shallow or wet soils), weather, and building beetle populations; and (b) they cannot track the long-term influence of climate change on either autogenic, or allogenic growth factors.

Avalanche and rockfall protective function

Because Norway spruce predominates in the upper montane and subalpine belt, it can be quite effective against the release of avalanches (although not on their transit), provided that stands meet given structure and density standards (Motta and Haudemand 2000). Like wind damage, required stand structures can be represented as risk zones on the DMD (Fig. 8). Although individual-tree resistance parameters are similar to those required for windfirmness, effective stand structures differ because open stands with thicker trees are more prone to avalanche release due to the presence of tree-free gaps (Meyer-Grass and Schneebeli 1992; Bebi et al. 2009). By experimenting with different management regimes on the DMD (Fig. 8), we concluded that Norway spruce stands could remain within a low-risk zone for as long as 60 years, provided that site index is not too high, such as most subalpine stands (e.g., 25.2 m on average for stands at elevations >1,700 m on the Eastern Alps, data from Cantiani et al. 2000). Even for high potential productivity, the low-risk period could extend up to 30 years, which would allow for spatial planning of silvicultural interventions in avalanche-prone catchments, with a goal to maintain some proportion of Norway spruce stands in the catchment as active protection forests. Boundaries for the low-risk zone could be extended by relaxing the tree slenderness or competitive status requirements. However, this would come at the expense of individual vitality and stand-scale resistance. When the degree of tree clumping is high, it is very difficult to contrast the presence of gaps large enough to trigger potentially hazardous snow movements. Management can mitigate the tendency for large gap creation at lower elevations. For example, simulations by Cordonnier et al. (2008) suggest that by creating small gaps every 20 years, uneven-aged structure can be initiated, thereby increasing the protective function of mountain Norway spruce stands in the western Alps. In subalpine forests, which exhibit clumped spatial arrangements (Motta and Lingua 2005), stabilization of avalanche channels has to be pursued by alternative means or structures. Similar considerations

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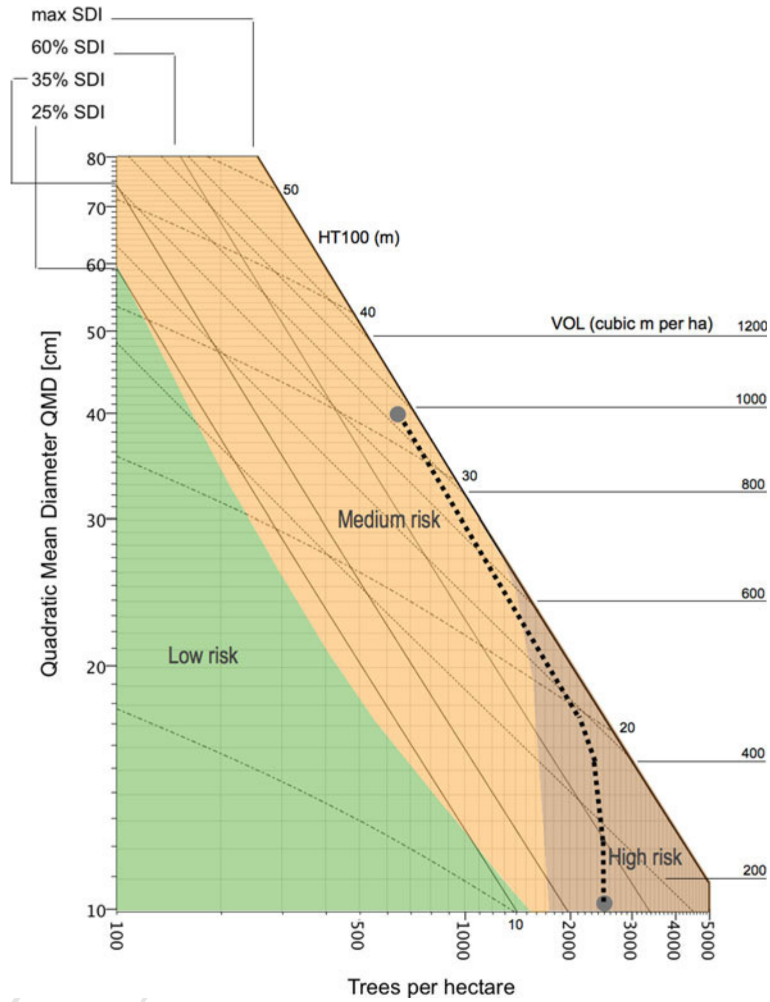

Fig. 7 DMD and risk zones for windfirmness of Norway spruce stands. Starting stand conditions, EOR, and unmanaged stand trajectory as in working example for Fig. 6

could be made for rockfall, albeit using different thresholds on the DMD (Vacchiano et al. 2008).

Resistance to spruce bark beetle

In central-southern Europe, spruce bark beetle outbreaks are a part of the natural disturbance regimes of Norway spruce forests (Svoboda et al. 2012). However, mortality induced by bark beetle may severely alter structure and functionality of stands that are managed for important ecosystem services, such as protection from geological hazards (Amman 2006) or water quality (Huber 2005). Outbreaks are primarily triggered by climate and abundance of infestation source such as recent deadwood; droughts, windthrow, or pollution may decrease tree vigor and increase susceptibility, although evidence is still contradictory to this extent (Baier 1996; Dutilleul et al. 2000; Wermelinger 2004). Norway spruce trees have recently been found to be potentially more resistant to spruce bark beetle when the density of foliage or foliage packing is high (Jakuš et al. 2011), presumably as a result of the inability of adults to reach the stem. This suggests Norway spruce trees that maintain longer crowns *throughout stand development* are more likely to resist spruce bark beetle infestation. Although the DMD was developed using stand-level data, it is relatively easy to visualize stand–density combinations necessary to maintain long live crowns. If we were to assume that full canopy closure in Norway spruce stands occurs at 25–35 % SDI (Long 1985), we would seek to maintain stands on average below that level when portrayed on the DMD. While it may be possible to enhance individual-tree growth and potentially resist the beetle under this regime, it would come at the expense of stand-level growth and would almost certainly result in low-quality logs by the EOR because of large lower branches. This shows that trade-offs associated with management goals must be considered. Fortunately, they can be simultaneously portrayed on the DMD.

An overlay of low-risk zones from Figs. 7 and 8 demonstrates potential conflicting management goals or desired conditions that cannot be simultaneously maximized. The ability of Norway spruce stands to meet various management

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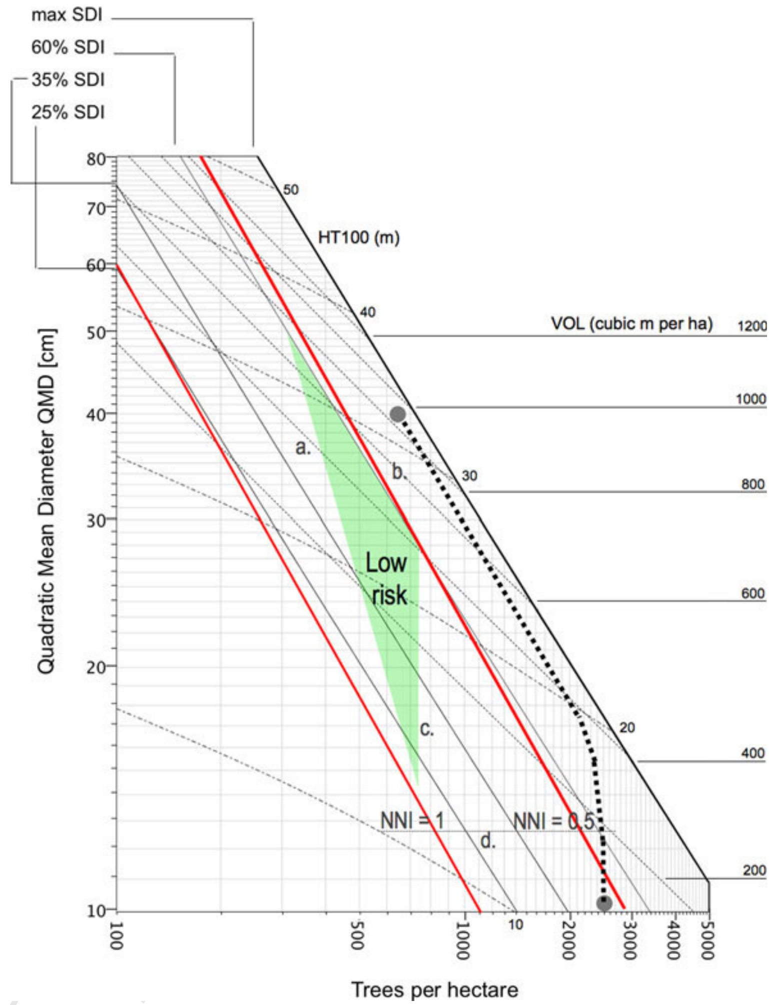

Fig. 8 Low-risk zone for avalanche release hazard (slope = 35°). Low-risk boundaries express: *a* minimum basal area, *b* SDI for minimum crown ratio, *c* maximum HT_{100}/DD ratio. *d*—*red lines* maximum gap size for NNI = 0.5 (clumped tree spatial pattern) and 1 (random pattern) according to Eq. 7. Starting stand conditions, EOR, and unmanaged stand trajectory as in working example for Fig. 6

objectives can be assessed on the DMD provided that associated requirements can be expressed by average (or distributional) stand parameters. Possibilities include habitat quality for ungulates (Smith and Long 1987) and birds (Shaw and Long 2007). For example, the DMD can be used to project which density regime would promote tree growth of the dominant cohort and speed up the creation of future veteran trees that will serve as habitat when alive or standing dead or to estimate the time necessary for conversion from monocultures to mixed natural forest by using the MSB to manage for time required to form stable canopy gaps.

Conclusion

The proposed DMD represents a marked improvement in Norway spruce density management over conventional approaches, because it characterizes ecological processes that drive growth and mortality. Statistical results for the stand-scale DMD suggest it is adequately robust for use over the geographic area covered by our analysis. The DMD allows the silviculturist to graphically display current stand conditions and project stand development after treatment with respect to density-dependent mortality and susceptibility of stand structure to natural hazards or disturbance agents. Multiple management scenarios can be simultaneously portrayed on the DMD to assess which EOR goals in terms of tree size, density, volume, and ecosystem services can be met, how much time is required to meet them, and how long they can be maintained by management.

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