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A density management diagram for Scots pine (*Pinus sylvestris* L.): A tool for assessing the forest's protective effect

Giorgio Vacchiano [a,*], Renzo Motta [a], James N. Long [b], John D. Shaw [c]

[a] Dipartimento Agroselviter, Università di Torino, Via Leonardo da Vinci 44, 10095 Grugliasco, TO, Italy
[b] Department of Wildland Resources and Ecology Center, Utah State University, 5230 Old Main Hill, Logan, UT 84322, USA
[c] Forest Inventory and Analysis, Rocky Mountain Research Station, 507 25th Street, Ogden, UT 84401, USA

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Abstract

Density management diagrams (DMD) are graphical tools used in the design of silvicultural regimes in even-aged forests. They depict the relationship between stand density, average tree size, stand yield and dominant height, based upon relevant ecological and allometric relationships such as the self-thinning rule, the yield-density effect, and site index curves. DMD effectively summarize stand structural descriptors, and are therefore helpful in determining stand characteristics needed to achieve a range of management goals.

We constructed a DMD for Scots pine (*Pinus sylvestris* L.) forests in the western Italian Alps. We used 210 sample plots from a region-wide forest inventory to determine the maximum density line and volume and top height isolines. Site index curves were used to assess the time taken by stands to progress along their development trajectories.

The protection provided by Scots pine stands is most effective against rockfall, due to the frequent occurrence of such forests in active source or transition areas. We used the DMD to identify combinations of size and density representing optimal and sub-optimal protection from rockfall. An actual pine stand was used as a case study to illustrate how the diagram can be used to assess current functionality of the forest, forecast its likely development and compare alternative management strategies.

Keywords: Density management diagram (DMD); *Pinus sylvestris* L.; Protection forests; Rockfall; Natural hazards

1. Introduction

Scots pine (*Pinus sylvestris* L.) is a stress tolerant, light demanding, usually early-seral species (Richardson, 1998). Scots pine forests cover in Europe more than 28 million hectares (20% of total forested area) (Mason and Alía, 2000). Pine forests play different ecological roles, ranging from pioneering communities established on abandoned agricultural land in parts of western Europe to stable communities in Central and Northern EU as well as forests on dry, marginal sites in the Alps and the Pyrenees, where it was relegated by a century-long forest management history (Białobok, 1975; Ozenda, 1985).

Increasing population density and emerging tourism in the alpine environment have resulted in an increased demand for hydrological services and protection of settlements, activities and roads from natural hazards. This has, in turn, focused the attention on the protective function of mountain forests (Krauchi et al., 2000; Motta and Haudemand, 2000). Due to their wide geographical distribution and the increase in forest cover following post-war agricultural land abandonment (Barbéro et al., 1998; Poyatos et al., 2003; Poschlod et al., 2005; Caplat et al., 2006; Garbarino et al., 2006), mountain Scots pine stands have a priority role in both general protection from erosion and direct protection of human activities from natural hazards.

A forest plays a direct protective function if it protects people, buildings and infrastructure against the impact of natural hazards such as avalanches or rockfall (Mayer and Ott, 1991). Among the natural hazards commonly affecting mountain areas, we believe the protection provided by Scots pine stands to be most effective against rockfall, due to the frequent occurrence of such forests in source or transition areas for falling boulders. The forest here plays its role by (1) preventing triggering of the event in source areas; (2) reducing kinetic energy of falling boulders in the transition zone; (3)

* Corresponding author. Tel.: +39 11 6705536; fax: +39 11 6705556.
E-mail address: giorgio.vacchiano@unito.it (G. Vacchiano).

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shortening distance traveled by rocks in accumulation areas (Dorren et al., 2004, 2007; Regione Autonoma Valle d'Aosta and Regione Piemonte, 2006).

Several attempts have been made to describe structural features contributing to the protective function of a forest stand (Wasser and Frehner, 1996; Brauner et al., 2005; Frehner et al., 2005; Wehrli et al., 2006). Nevertheless, most approaches were based on a ‘‘snapshot’’ view of the forest, and granted little attention to the consequences of stand development on the stability of the protective role through time.

Density management diagrams (DMD) are graphical models of even-aged stand dynamics (Newton, 1997). They reflect fundamental relationships involving tree size, stand density, site occupancy, and self-thinning (Jack and Long, 1996). They portray competition-induced mortality dynamics allowing users to forecast stand development. Both current, and desired future, stand structure can be plotted on the DMD. Alternative management strategies to accomplish diverse objectives can therefore be devised and effectively compared at a glance (Shaw and Long, 2007).

Jack and Long (1996) and Newton (1997) gave useful reviews of the history and features of DMD. Such diagrams exist for a number of species in North America (e.g., Drew and Flewelling, 1979; McCarter and Long, 1986; Williams, 1994; Spathelf and Schneider, 2000; Long and Shaw, 2005; Sharma and Zhang, 2007; Shaw and Long, 2007), Central and South America (Márquez-Linares and Alvarez-Zagoya, 1995; Chauchard et al., 2001), Asia (Ando, 1962, 1968; Tadaki, 1963; Kumar et al., 1995), and Africa (Onyekwelu et al., 2003; Biber et al., 2004). To date DMD exist for only a few European species (Sales Luis and Fonseca, 2004; Anta and González, 2005), and have not yet been used for describing structural characteristics of protection forests.

Careful planning and management is required to sustain functioning protection forests. These forests usually serve other functions, such as wood production or recreation, which may result in conflicting management objectives. Therefore, managers often seek for decision supports to handle these conflicting purposes in an efficient and sustainable way (Brauner et al., 2005).

The aim of this research is to develop a DMD for Scots pine in the western Italian Alps, and test its suitability for assessment of present and future effectiveness of direct protection function. We reviewed the assumptions needed to apply DMD as a silvicultural tool, and evaluated available references to optimal stand and tree parameters for maximizing direct protection from rockfall. Our intent was to characterize on the DMD a suitability zone (*sensu* Shaw and Long, 2007) for optimal protection. Last, a case study illustrated how silvicultural management strategies aimed at improving stand functionality can be effectively represented on the diagram.

2. Methods I: constructing the DMD

2.1. Study area and data

A forest inventory of Piemonte and Valle d'Aosta regions (Fig. 1) provided data necessary for the construction of the DMD. Base grid size is 500 m; sample plots are circular, with a radius between 8 and 15 m depending on overstory density (Camerano et al., 2007; Gottero et al., 2007). In each plot, the following variables were recorded: UTM coordinates, eleva-

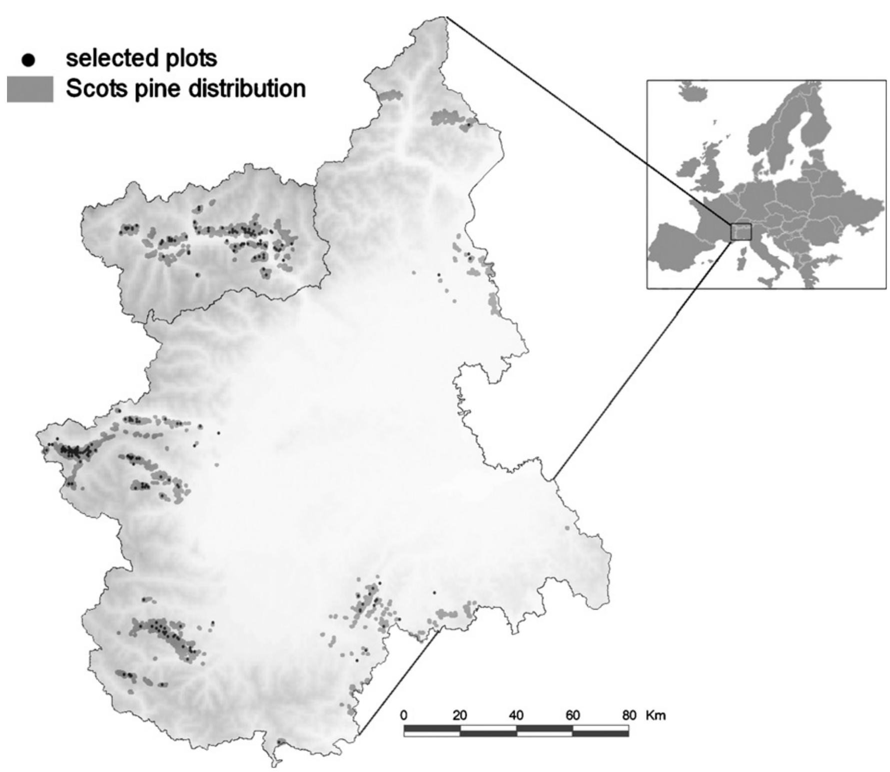

Fig. 1. Scots pine distribution in the study area and location of inventory plots selected for DMD fitting.

tion, slope, forest cover type, stand structure and developmental stage, species and diameter at breast height (dbh) of all living individuals larger than 7.5 cm, height of the tree closest to the plot center, percent canopy cover, number of stumps, snags and seedlings, forest health conditions, pre-eminent forest function and management priority. The database encompassed 457 plots where Scots pine was recorded as the dominant forest cover type. We computed stand density, basal area on a per hectare basis and quadratic mean diameter (QMD) for Scots pine and for all species combined. We calculated Reineke's (1933) stand density index (SDI) as modified by Daniel et al. (1979) and in the summation form suggested by Long and Daniel (1990):

$$\mathrm{SDI} = N\left(\frac{\mathrm{QMD}}{25}\right)^{1.6} \tag{1}$$

$$\mathrm{SDI_{SUM}} = \sum\left(N_i\left(\frac{\mathrm{dbh}_i}{25}\right)^{1.6}\right) \tag{2}$$

where SDI is stand density index, N is the number of trees per hectare, QMD is quadratic mean diameter at breast height (cm), N_i is the number of trees per hectare represented by the i-th tree, dbh_i is breast height diameter of the i-th tree in the plot (cm).

The two methods produce values of SDI essentially equal for even-aged stands, but more divergent with increasing skewness of the diameter distribution (Shaw, 2000; Ducey and Larson, 2003). We computed the ratio of $\mathrm{SDI_{SUM}}$ to SDI for the purpose of separating relatively even-aged stands from stands with more complex structures (Long and Shaw, 2005).

For the construction of the DMD and the evaluation of its inherent allometric relationships, inventory plots were selected according to the following criteria (modified from Shaw and Long, 2007):

(1) Species composition: more than 70% of basal area represented by Scots pine,
(2) Even-agedness: $\mathrm{SDI_{SUM}}$ to SDI ratio higher than 0.9;
(3) Management impact: number of stumps less than 10% of living stems;
(4) Sampling intensity: more than 10 measured trees per plot.

Selected stands, whose characteristics are summarized in Table 1, covered most sectors of Scots pine distribution in the study region (Fig. 1), save for a few areas that were excluded due to the high occurrence of pine-broadleaves mixed stands or because of intense management.

Table 1
Summary of sample plots used for the construction of the DMD

	Mean	Minimum	Maximum	S. D.
Plot area (m^2)	359	142	707	126.8
QMD (cm)	21.6	10.7	45.4	5.59
Density (trees ha^{-1})	967	152	3318	534.9
Basal area (m^2 ha^{-1})	32.18	5.33	89.75	15.162
Scots pine on BA (%)	93.1	70.0	100.0	8.39
Height of largest tree (m)	13.8	8.1	21.8	2.52
Standing volume (m^3 ha^{-1})[a]	226.1	25.9	733.7	129.37

[a] Volume equations were available only for 131 plots.

2.2. Size-density boundary

Reineke's SDI was computed by the summation method for each plot assuming a self-thinning slope of 1.6, represented by the power coefficient in Eqs. (1) and (2). The 1.6th power for the relationship between mean tree size and density was suggested by Reineke (1933) to be invariant for all plant communities experiencing maximum crowding. Due to limited plot size, certain plots may be located in overstocked patches that were not continuous beyond the plot boundary (Wilson et al., 1999). We estimated the maximum SDI ($\mathrm{SDI_{max}}$) as the 98th percentile in the $\mathrm{SDI_{SUM}}$ frequency distribution, a threshold we believe to better represent the stand-scale maximum attainable stocking. The maximum size-density boundary represents maximum achievable density for a given mean size, i.e., maximum exploitation of available growing space, and therefore maximum competition intensity (Yoda et al., 1963). We represented the maximum size-density boundary as a 1.6-power function fitted through QMD-density combinations resulting in maximum SDI.

Several authors reported the evidence of a fall-off from the linear size-density boundary in older stands (White and Harper, 1970; Zeide, 1987; Cao et al., 2000; Shaw and Long, 2007), a pattern attributed both to the inability of old trees to fully recapture available resources following the death of other large trees, and to crown shyness proportionally increasing with tree height (Assmann, 1970; Long and Smith, 1992). Our data were insufficient to establish the presence or absence of such "mature stand boundary" (Shaw and Long, 2007); we assumed the maximum size-density relationship to be linear across the entire range of sizes and densities represented.

Relative density, expressed by the percent ratio between plot-level and maximum $\mathrm{SDI_{SUM}}$, provided an estimate of competition intensity in each stand. The usefulness of SDI as a relative density index is supported by its independence from stand age and site quality (Reineke, 1933). Relative density thresholds have been suggested to indicate crown closure, initiation of competitive dynamics, and the onset of self-thinning – the so-called zone of imminent competition mortality (Drew and Flewelling, 1979; Long, 1985). Lines representing such thresholds (0.25, 0.35 and 0.60 times $\mathrm{SDI_{max}}$, respectively, according to suggestions by Long, 1985) were plotted on the DMD to readily assess relative density of actual and projected stands. Size-density combinations indicative of crown closure were alternatively computed for each stand from an allometric relationship between stem diameter and crown width for open-grown trees (Hasenauer, 1997), assuming a uniform diameter distribution and triangular spacing between trees.

2.3. Top height and volume isolines

When represented on the DMD, dominant height can be used jointly with an appropriate site index curve to assess the time needed for projected stands to reach given structures, developmental stages or yields, thus introducing the temporal dimension in the diagram (Jack and Long, 1996). In order to plot such variable on the DMD we first modeled individual tree height as a function of dbh and plot basal area (which was shown by preliminary testing to be the most informative competition-related predictor, as compared to stand density and plot basal area in larger trees) by the following linear model:

$$h_i = a_0 + a_1\,\mathrm{BA} + a_2 \log \mathrm{dbh}_i \tag{3}$$

where h_i is tree total height (m), BA is plot basal area ($\mathrm{m}^2\ \mathrm{ha}^{-1}$), dbh_i is tree diameter at breast height (cm), a_0, a_1 and a_2 are model parameters.

The model was fit on pine trees systematically sampled for height ($n = 348$), excluding trees with poor stem quality and with unrealistic height-to-diameter ratio (<20 or >200), as compared with an ancillary dataset of reference trees from the same region (Nosenzo, unpublished data).

Stand dominant height was computed as the mean height of the 100 thickest trees per hectare (Sharma et al., 2002). Selected stands were mostly pure and pine-dominated, thus the error due to extending the validity of the pine-specific height–diameter model to other species was minimal. Since the ratio of stand dominant height to QMD was best modeled by an inverse logarithmic function of stand density, we included the three variables in the following nonlinear regression model:

$$\mathrm{QMD} = H_{100}(b_1 - b_2 \log N) \tag{4}$$

where QMD is quadratic mean diameter at breast height (cm), H_{100} is stand top height, i.e., the mean height of the 100 thickest trees per hectare (m), N is stand density (trees ha^{-1}), b_1 and b_2 are model parameters.

The sign of coefficient b_2 was constrained as negative in the nonlinear fit in order to account for the inverse influence of stand density on tree diameter. For a given height, trees growing in dense stands exhibit smaller diameters than those growing in sparser stands, because of higher competition among individuals (Temesgen and von Gadow, 2004). Substituting age for height and mean tree volume for diameter leads to an alternative formulation of the yield-density effect theorized by Shinozaki and Kira (1956).

Single-tree volume equations provided by the regional inventory and parameterized for different species and fertility classes were used to compute plot volume on a per-hectare basis. Stand yield was then expressed as a function of QMD and density in order to generate volume isolines:

$$\mathrm{VOL} = c_1 N(\mathrm{QMD} - c_2)^{c_3} \tag{5}$$

where VOL is total standing volume ($\mathrm{m}^3\ \mathrm{ha}^{-1}$), N is number of trees per hectare, QMD is quadratic mean diameter at breast height (cm), c_1, c_2 and c_3 are model parameters.

The equation comes in the form of a shifted-power function, which best modeled the relationship between mean tree volume and QMD, and yields slightly concave volume curves when plotted on the DMD (compare with McCarter and Long, 1986).

Allometric relationships portrayed on the DMD were assumed invariant across all sites (Weiner, 2004). A curve-fitting software (Hyams, 1997) aided in choosing the most suitable model forms. All models were fitted using the nonlinear regression module of SPSS (SPSS Inc., 2004) and assessed for parameter significance and overall goodness-of-fit by computing adjusted R^2 and root mean square error (RMSE). Model residuals were tested for normality and independence from predictors and from relevant stand and site descriptors.

3. Results I: plotting the DMD

After screening, 210 sample plots were retained for determination of the maximum size-density line. Maximum SDI for Scots pine stands in the sample was 1440. A long-standing concern centers on the most appropriate method for parameter estimation of the limiting self-thinning equation (Zhang et al., 2005), a difficult task when repeated inventory measurements are not available (Shaw, 2006). In a given sample only a fraction of stands are in a true self-thinning mode, the rest being understocked for a number of reasons, e.g., insufficient regeneration density or intense disturbance impact (Tang et al., 1994). Application of a binning method, i.e., improving selection objectivity by choosing one data point of maximum tree size for each one of several intervals of equal log-density width (Bi and Turvey, 1997; Vacchiano et al., 2005) yielded a self-thinning slope of −1.87 (Fig. 2), with Reineke's slope of −1.6 well within a 95% confidence envelope.

The Second National Swiss Forest Inventory (WSL, 2005) reported, for pure Scots pine plots (>70% relative basal area) in the Alpine region, a $\mathrm{SDI}_{\mathrm{max}}$ of 1348, as represented by the 98th percentile of the SDI distribution. Del Río et al. (2001) obtained a $\mathrm{SDI}_{\mathrm{max}}$ of 1444 for Scots pine in Spain, although they computed a different self-thinning slope. Other referenced maximum SDI for Scots pine in Europe range from 840 (computed from Hynynen, 1993) to 1454 (computed from Palahí et al., 2002). Even though the datasets used in these studies differed in stand origin (planted or naturally established), management intensity, degree of stocking, and plot selection criteria, most $\mathrm{SDI}_{\mathrm{max}}$ estimates were consistent with the present one. We compared our maximum against available yield tables for Scots pine in Europe (Wiedemann, 1949; Décourt, 1965; Hamilton and Christie, 1971; Marschall, 1976; Thren, 1987; Jansen et al., 1996), where SDI was computed from QMD-density combinations for the highest yield level (including crop trees and removals). The estimate from the current study was 17–74% higher than SDI from yield tables.

According to Reineke (1933), site fertility only effects the speed of advancement along the self-thinning trajectory. Other sources, however, suggested that maximum potential density is to be understood as a site property (Assmann, 1970; Sterba, 1987). Different site qualities have often been associated to different $\mathrm{SDI}_{\mathrm{max}}$, by varying either the intercept or the slope of the self-thinning line (Sterba, 1981; Hynynen, 1993; Morris, 2002). A one-way ANOVA showed significant differences between mean $\mathrm{SDI}_{\mathrm{SUM}}$ values ($P < 0.05$) grouped by forest site type (Camerano et al., 2004). However, we could not draw definitive conclusions, since sample size was very small (3 to 63 data per site type) and because mean SDI is likely to be affected by management history and age class distribution of the population being sampled. Therefore, we defined a single

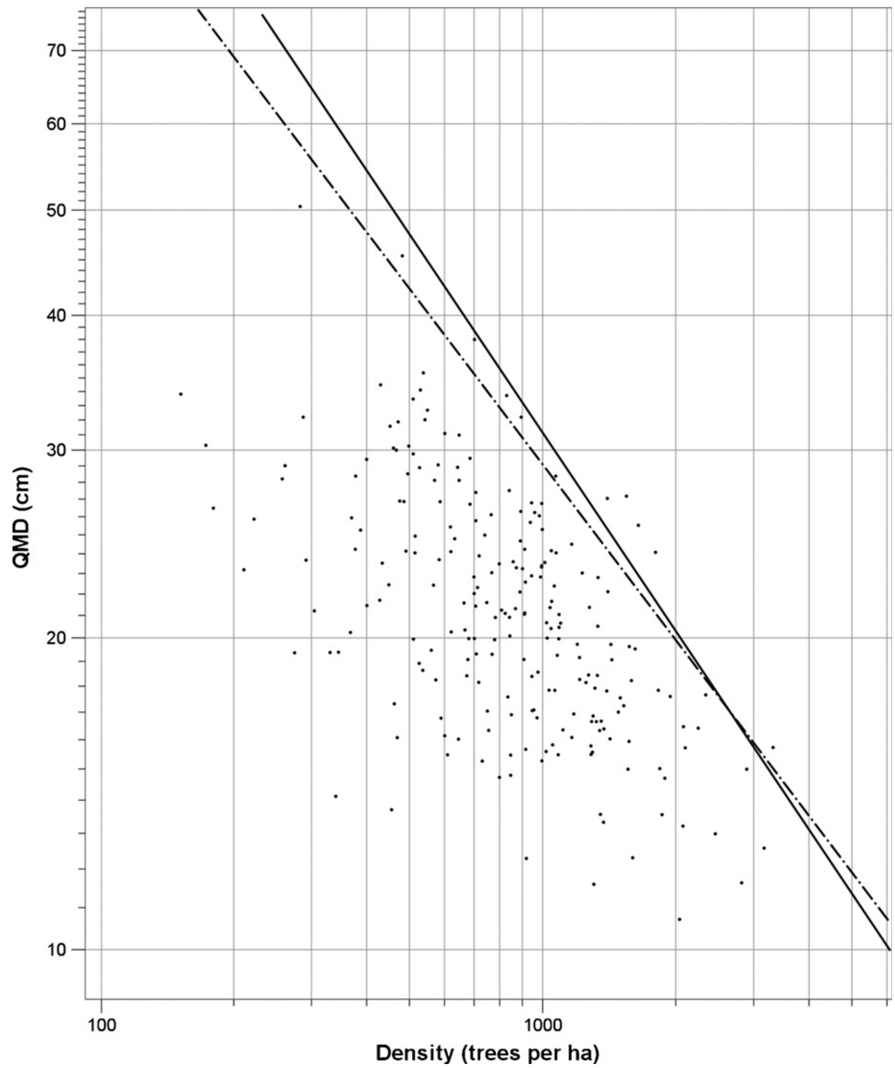

Fig. 2. Size-density combinations for the 210 plots included in the data set. Continuous line: maximum self-thinning boundary for SDI = 1440, slope of −1.6. Points above the line are characterized by size-density combinations beyond the 98th percentile of the SDI frequency distribution. Dashed line: self-thinning boundary computed by ordinary least square regression between stands with maximum QMD in 5 log-density classes. SDI computed by the binning method is 1310, i.e., 91% of SDI_{max}.

SDI_{max} value for all the plots, holding constant both the slope and the intercept of the self-thinning line constant.

Relative SDI (i.e., the ratio between observed and maximum SDI) ranged between 0.09 and 1.00 for all Scots pine stands ($n = 457$). In most cases (50%) relative SDI ranged between 0.35 and 0.60; only 19% of the stands had a relative SDI greater than 0.60 (Fig. 3). Land use changes have likely played a major influence in shaping stand structure: many stands that had established on recently abandoned areas have not undergone self-thinning yet, but may soon be expected to do so (e.g., 40% of our stands had relative SDI greater than 50%).

Relative SDI associated with canopy closure ranged from 0.13 to 0.66. The size-density relationship marking canopy closure-level crowding was steeper than the maximum size-density boundary, showing that the relation between canopy cover and the onset of competition must change with other stand variables, e.g., increasing stand height.

Table 2 summarizes best-fit estimates for Eqs. (3)–(5); the isolines plotted on the DMD cover the full range of top heights

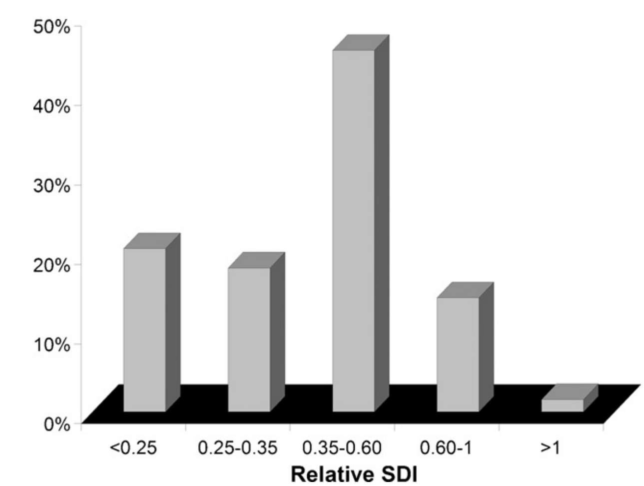

Fig. 3. Frequency distribution of relative density for SDI_{max} = 1440. Relative density classes according to Long (1985). Occasionally, highly crowded plots may attain size-density combinations higher than what overall stand conditions would allow (hence the values higher than 1).

Table 2
Nonlinear regression fit for allometric Eqs. (3)–(5)

	a_0	a_1	a_2	Adjusted R^2	RMSE
Eq. (3) $h_i = a_0 + a_1\mathrm{BA} + a_2 \log \mathrm{dbh}_i$					
Estimate	−9.306	0.099	5.763	0.491	±2.913 m
Asymptotic S.E.	1.371	0.011	0.445		
	b_1	b_2		Adjusted R^2	RMSE
Eq. (4) $\mathrm{QMD} = H_{100}(b_1 - b_2 \ln N)$					
Estimate	4.927	0.498		0.952	±0.755 cm
Asymptotic S.E.	0.078	0.012			
	c_1	c_2	c_3	Adjusted R^2	RMSE
Eq. (5)[a] $\mathrm{VOL} = c_1 N(\mathrm{QMD} - c_2)^{c_3}$					
Estimate	0.001	5.057	1.935	0.952	±263.27 $m^3\,ha^{-1}$
Asymptotic S.E.	0.001	1.202	0.128		

[a] Volume equations were available only for 131 plots.

(5 to 30 m) and the most common classes of standing volume (100 to 500 $m^3\,ha^{-1}$) measured in the selected plots.

All regression parameters were significant at the 95% confidence level. Residuals were normally distributed and unbiased against predictors. Nevertheless, we found some stand descriptors to have a significant influence on the height-diameter curve, namely elevation and stand age (both positively correlated to tree height residuals), aspect (stands on flat areas had higher-than-predicted top heights), site productivity class and forest cover type. Stand volume, on the other hand, was unbiased but characterized by a high prediction error (RMSE), depending on a few extreme outliers and most evident when representing mean bias in each forest district (Fig. 4). These results suggest users must confront with the choice between an average, wide-scale albeit rough model, and recurring to separate diagrams for different locations, to better capture local variability of allometric relationships. The full DMD for the study area is represented in Fig. 5.

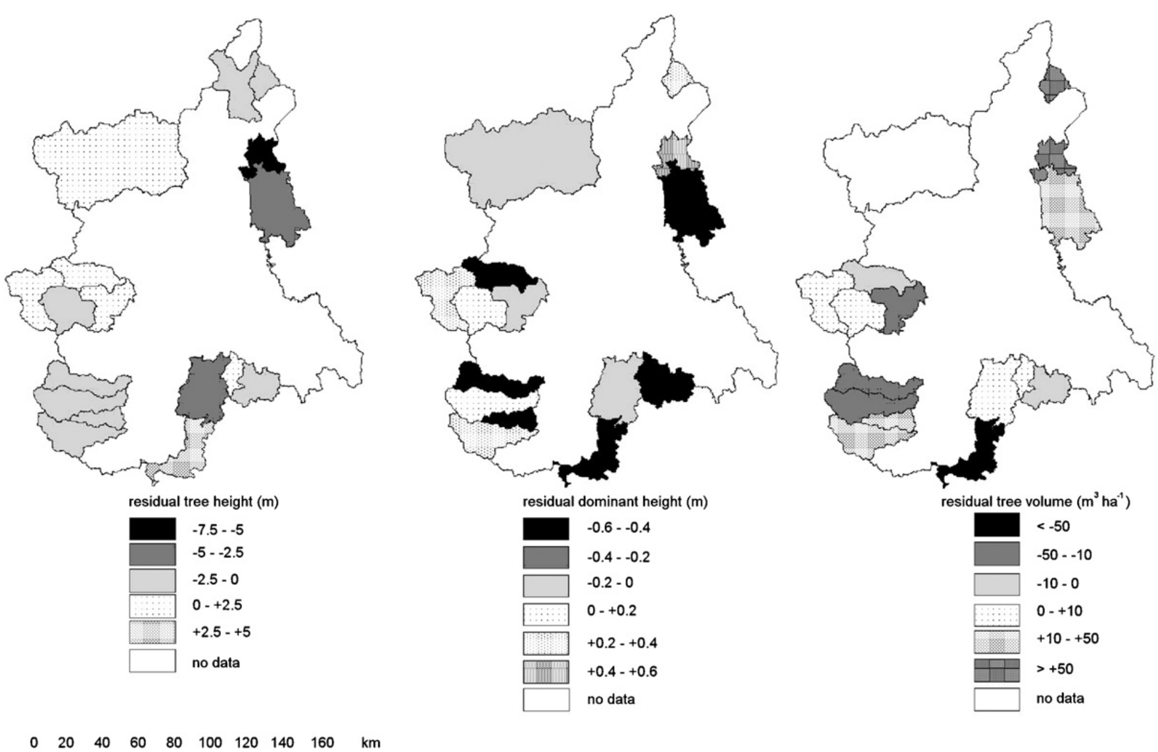

Fig. 4. Mean prediction error of allometric models for tree height, stand top height and standing volume, computed by forest district. A negative residual indicates underprediction by the model.

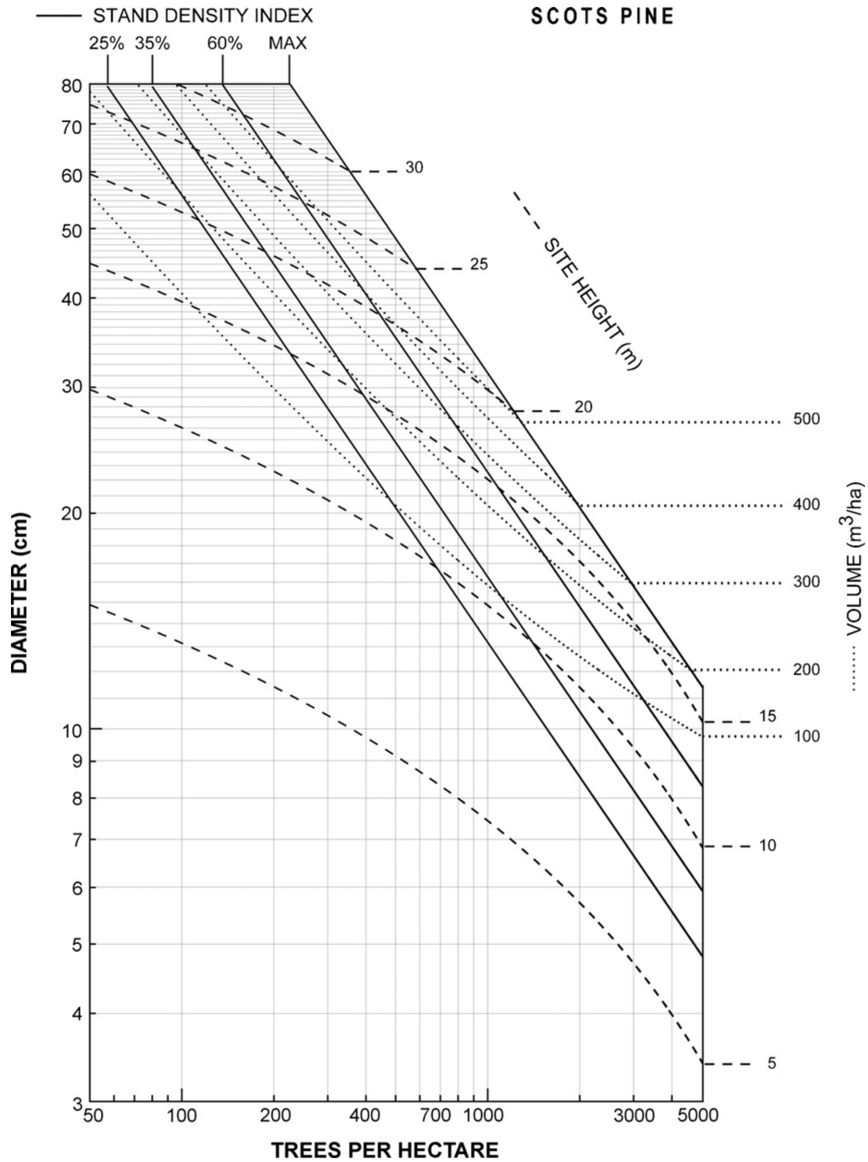

Fig. 5. Density management diagram for Scots pine in the western Italian Alps.

4. Methods II: a case study

Management of direct protection forests is aimed at maintaining or ameliorating stand structures allowing acceptable reduction of the natural hazard (Motta and Haudemand, 2000). In order to illustrate the advantages of DMD in identifying management goals and design silvicultural strategies for specific stands, we superimposed on the diagram a ''suitability zone'' enclosing all combinations of size and density fulfilling an effective protection against rockfall. An actual pine stand was then used as a case study to illustrate how the diagram can help assessing current functionality of the forest and planning for its future management.

We searched available literature for indications on structural parameters of forests fulfilling direct protection against rockfall (Wasser and Frehner, 1996; Dotta and Motta, 2000; Mitchell, 2000; Brändli and Herold, 2001; Frehner et al., 2005; Regione Autonoma Valle d'Aosta and Regione Piemonte, 2006), which are summarized by the following (number in parentheses express criteria adopted for minimal, rather than optimal, protection):

(1) Species composition: relative contribution of broadleaves higher than 30% (10%);
(2) Stand density: more than 400 (300) trees per hectare;
(3) Vertical structure: two-layered, sufficient viable trees in two different stages of development;
(4) Canopy cover: higher than 60%;
(5) Gaps in the stand: mean tree free distance (MTFD) <30 m. MTFD represents the probable mean distance between two tree-rock impacts in a forest stand (Perret et al., 2004; Dorren et al., 2005). According to Gsteiger (1989),

$$\mathrm{MTFD} = \frac{A}{N d_{\mathrm{rock}} + \sum \mathrm{dbh}_i} \qquad (6)$$

where A is stand area (m^2), d_{rock} is the relevant diameter of falling boulders (m), i.e., 0.3 m (0.5 m for minimal protection), N is stand density, Σdbh_i is the sum of tree dbh (m), here computed by multiplying QMD by tree density.

(6) QMD: larger than 0.3 times the diameter of the target boulder;

(7) Tree slenderness: lower than 80 (90) in dominant trees. A slenderness boundary may be represented on the DMD, substituting for the height term in Eq. (4);

(8) Live crown ratio: higher than 40% (30%) in trees or cluster of trees supporting the stability of the stand. A relative SDI of 0.50 should ensure a mean live crown ratio higher than 40% (0.60 and 30% respectively for minimal protection), a figure representing a generally acceptable level of individual tree vigor (Long, 1985);

(9) SDI: ranging from 600 to 1000 in order to avoid both excessive openness of the stand and stability threats due to crowding; this requirement is automatically met by implementing the previous indications.

Where applicable, tree and stand structural requirements were plotted on the DMD in order to enclose a suitability zone for rockfall protection. The transition from non-effective to fully functional structures can be smoothed out by assigning weights proportional to the protective effect associated with different values of the structural parameters under consideration. Each functionality zone can then be characterized by a synthetic index of direct protection which is the sum of the weights (Motta and Haudemand, 2000). We adopted a simplified weighting scheme with a two-value scale,

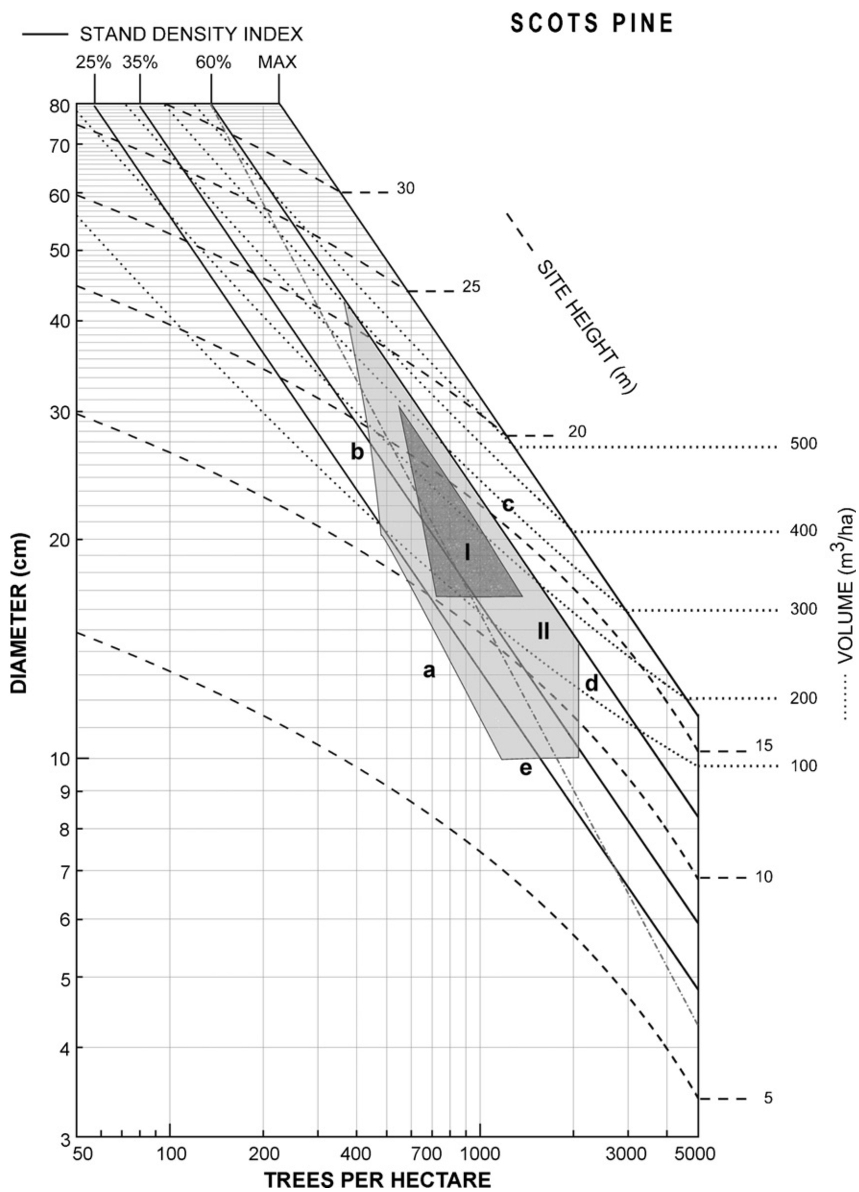

Fig. 6. Suitability zone for optimal (I) and minimal (II) protection from rockfall. Size-density combinations determining complete canopy closure (dash and dotted line) are superimposed on the DMD. Suitability zones are defined by (a) minimum crown closure; (b) minimum MTFD; (c) minimum crown ratio; (d) maximum tree slenderness; (e) minimum QMD.

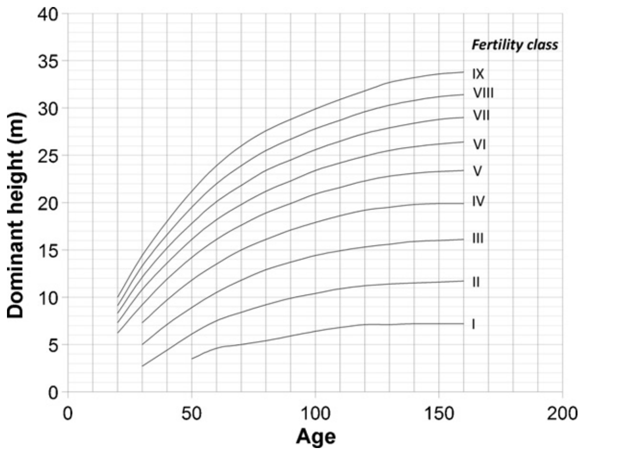

Fig. 7. Site index curves for Scots pine used in this study (adapted from Wiedemann, 1949). Model form and measures of statistical significance were not specified by the source.

representing optimal and minimum acceptable protection (Fig. 6).

The case study stand is located in the municipality of Antey Saint-André (45°48′00″N; 7°36′00″E) at an elevation of 1200 m a.s.l. A permanent sample plot (100 m × 80 m) has been established in the transition zone of a rockfall-prone slope. Scots pine represents 78% of the total number of trees, with a QMD of 22.7 cm and an overall density of 995 trees ha^{-1} (dbh > 7.5 cm). Mean live crown ratio is 40%; mean crown cover is 51%, some gaps being sparsely located on small scree slopes.

The estimate of standing volume provided by the DMD was very close to the ground truth (257 and 252 $m^3\ ha^{-1}$, respectively). Conversely, stand top height suffered from a large underestimation bias, that was likely due to the influence of less fertile stands in the calibration dataset.

Since the oldest trees were found to be 160 years old (Berretti, personal communication), we estimated mean stand age to be 110 years. No site index curves were available for the study area, therefore we inferred them from available yield tables for Scots pine (Wiedemann, 1949) (Fig. 7). If Wiedemann's site indices were assumed to be appropriate, the dominant height computed by Eq. (4) would put the stand close to fertility class III, or SI = 14 m (dominant height at a base age of 100 years).

To explore options for sustaining the protective function, we modeled on the DMD three management options: a single-entry low thinning, a double-entry low thinning, and a selection thinning (i.e., options (ii), (iii), and (iv) in Table 3, where option (i) represents no management), and compared their outcome in terms of end-of-rotation yield, mean tree size and time spent by the stand in fulfillment of a direct protective role.

5. Results II and discussion

In the study area, 30% out of a total 19,201 ha of Scots pine stands are designated as protective forests, with 4000 ha performing a direct protective function (Regione Autonoma Valle d'Aosta and Regione Piemonte, 2006).

The case study stand is currently near the outer edge of the zone of minimum effective rockfall protection. Current competition levels (SDI = 890, relative SDI = 0.62) may soon result in increasing mortality rates, slowed tree growth, decreasing mean live crown ratio and an increasingly closed canopy, with an higher risk of damage due to biotic or abiotic disturbances. Evidence of ongoing self-thinning was found in the field: a high number of standing dead trees, regularly spaced surviving trees, a high mean stem slenderness (0.70, a value well-matched by DMD predictions) and a low mean live crown ratio. Individuals grown in a highly competitive environment will also suffer a reduction in individual vigor, which may further aggravate the negative impact of disturbance agents. All these factors would hamper stand stability and hinder the fulfillment of an effective rockfall protection in the near future.

Table 3
Comparison of density management alternatives: stand parameters at present time and after each silvicultural entry (computed from calibrated DMD relationships) and permanence in time of effective minimal or optimal rockfall protection

	Age[a]	H_{100} (m)	N (trees ha^{-1})	QMD (cm)	VOL[b] ($m^3\ ha^{-1}$)
Starting conditions	110	15	995	22.7	257
(i) Natural stand development[c]	160[d]	18	753	30	380
Time in optimal + minimal zone	0 + 0 years				
(ii) Low thinning (−10% VOL)	110	15	866	23	231
Time in optimal + minimal zone	0 + 25 years				
(iii) Selective thinning (−40% VOL)	110	13	645	22	154
Time in optimal + minimal zone	20 + indefinite[d]				
(iv) Before low thinning 2	130	15	600[e]	26	216
After low thinning 2	130	15	400	29	187
Time in optimal + minimal zone	20 + indefinite[d]				

[a] Estimated mean stand age. Time lapses are computed by using SI = 14 m (fertility class III).
[b] Volume estimated by DMD isolines (starting volume differs from true value).
[c] Estimated stand dynamics driven by self-thinning, up to a QMD of 30 cm and a relative density of 0.70.
[d] Stand top height lies outside the range determined by yield tables for the chosen fertility class.
[e] Density has been allowed a slight reduction from the predicted value even during competition-free stand development, due to the purported influence of rockfall disturbance.

The rapid deterioration of the protective effect of the forest may be avoided by implementing silvicultural measures. Thinning reduces competitive pressure and promotes tree vigor and stability. Thinning entries can be represented on the DMD by plotting their effects in terms of mean tree size, stand density and top height. A moderate thinning from below (i.e., with constant dominant height) removing 10% of standing total volume, as proposed by a panel of experts (Regione Autonoma Valle d'Aosta and Regione Piemonte, 2006), would impart to the stand a greater effective rockfall protection, and extend its functionality in time (as computed by site index curves).

A selective thinning would further prolong stand suitability for optimal and minimum rockfall protection. The proposed action involves removing 40% of standing mass and decreasing stand density and QMD so as to relocate the stand on the lower boundary of the optimal protection zone. Thinning from above has been suggested as a worthwhile practice in fertile Scots pine stands as compared to low thinnings (Favetta, 1996), whose low selectiveness may impede a timely response by trees of already mature age. An intense selection thinning pushing the stand back into the minimum protection zone might be the best choice, coupled to mitigation strategies for the higher rockfall hazard due to reduced density. Thinning in narrow strips perpendicular to the slope (if technically of economically feasible) or positioning temporary support measures, such as wooden fences or lying logs, are the most common practices.

Last, an additional low thinning, to be performed as soon as the stand again approaches the edge of the suitability zone, would allow the maintenance of constant crown closure throughout the rotation, mitigate the impact of logging activities on advance regeneration, and preserve slender trees from sudden isolation. The main drawbacks are represented by the high operation cost, due to both low quality and quantity of removals, and by the reduced growth response that mature trees would likely exhibit after such entry.

In modeling the consequences of silvicultural entries on the DMD, we assumed the changes following artificial thinning to be short-lived and not substantially affecting allometric relations during subsequent stand development (Drew and Flewelling, 1979; Smith, 1989). While any of the active management options should sustain the direct protective function for longer than the no-treatment option, the selection thinning regime promotes active protection for the longest time span. However, time predictions should be considered with caution, since age estimates are strongly dependent on the site index curve used in the analysis.

6. General remarks

As shown by our case study, a DMD for Scots pine forests incorporating a suitability zone for rockfall protection is useful in managing stands where such a function represents the prioritized silvicultural aim. The diagram allowed us to forecast the likely stand development should no management be carried out, and to compare the no-treatment option to different management strategies, whose timing and intensity could be planned based on relevant allometric relationships of the species under analysis. The usefulness of DMD in protection forests is thus manifold. They allow to assess current stand structural conditions, forecast future stand development, and compare the effectiveness of different silvicultural management strategies aimed at maximizing a direct protective function.

Some of the shortcomings that may arise when using DMD to assess forest protective function include: (i) a limited capability to model resilience, i.e., the power to quickly recover an efficient structure following adverse impacts (Grimm and Wissel, 1997; Brang, 2001). Potential for regeneration establishment could be indirectly taken into account by estimating the available growing space in the parent stand (e.g., Moore and Deiter, 1992; Naumburg and DeWald, 1999). Regeneration models (Pukkala, 1987; Prévosto et al., 2003; Castro et al., 2004) capable of assessing growing space requirements for the species of interest could help in designing regeneration suitability zones within a species' DMD; (ii) usability is limited to a geographic and structural range similar to that used for diagram calibration (Drew and Flewelling, 1977). This makes mixtures especially difficult to deal with, because the position of the self-thinning line and the estimate of overall growing space are species-specific parameter (Weller, 1987; Hynynen, 1993; Inoue et al., 2004; Pretzsch, 2006; but see, e.g., Puettmann et al., 1992; Solomon and Zhang, 2002 for successful representation of mixtures in DMD); (iii) the dynamics and management regimes described for the mean stand are not necessarily true or optimum for any particular stand (Drew and Flewelling, 1979), i.e., there is a choice to be made between generality and accuracy of the model. Hence, we consider the computation of local site index tables a high-priority task in order to achieve more accurate stand growth predictions. Moreover, the poor significance of some model functions, due to limited data availability, suggests the need of additional sampling to validate the allometric relationships that represent the "backbone" of the diagram, and eventually, the importance of a properly designed inventory for future extension of the diagram to other forest species.

Conversely, DMD are best applied when users need a large-scale, rapid tool to assess current and future forest functionality, by means of overlaying time-independent structural requirements with the likely development trajectory of the desired stands. The design of rockfall suitability zones is very sensitive to the criteria adopted; we suggest to define suitability zones based on multiple requirements, so as to devise more robust predictions. Ideally, forest ecosystems most effective against rockfall enter a steady state in which small patches with alternating developmental phases provide the forest with a collective stability, which is sub-optimal for protection on the short term, but optimal on the long term (Dorren et al., 2004). The most stable forest structure is a small-scale mosaic of all classes of tree size and age (Ott et al., 1997; Motta and Haudemand, 2000). A set of DMD would allow monitoring the functionality of each structural stage and anticipating the impact of management actions and disturbances on the stands that constitute such mosaic. We therefore suggest the use of DMD as an effective support to management planning in forests playing a direct protective role.

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