

Estimating the mechanical stability of *Pinus nigra* Arn. using an alternative approach across several plantations in central Italy

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Black pine has been used often in central and southern Italy to reforest mountainous areas depleted by the intensive use of natural resources. The main purpose of establishing pine forests in Italy was to protect the soil from excessive erosion, and also to facilitate the natural succession toward mixed forests with deciduous species. The most common silvicultural treatments in Europe currently aim at maximizing the stability of the stands and facilitating the transition from pure to mixed stands comprising a larger component of native tree species. In this work, we investigated the relationships between the living whorls number and four indexes of individual tree stability: the slenderness ratio, the crown depth, the crown projection, and an eccentricity index of the canopy. The data set used was composed of 1098 trees from ten black pine plantations located in central Italy. Our results demonstrate that the living whorls number can be handily used to predict the slenderness ratio with an error of 18%. A non-parametric model based on a reduced number of field measures was obtained as a support for thinning operations aimed at improving single tree stability.

Keywords: Black Pine, Tree Stability, Living Whorl Number, Slenderness Ratio, Crown Depth, Crown Projection, Crown Eccentricity

Introduction

In Central Europe, the Balkans, and Mediterranean countries black pine (*Pinus nigra* Arn.) is commonly planted for protection purposes (Bussotti 2002). In Italy, this practice was established at the national level in the 20th century in accordance with a policy that was developed to protect the land from erosion (Piermattei et al. 2012).

Black pine has been used often in central and southern Italy to reforest mountainous areas depleted by the intensive use of natural resources, especially during World War I and II. Toward the end of the 1970s, the mandatory requirement to reforest these areas using coniferous species was discontinued. In Italy, black pine occurs mostly in pure stands of even-aged forests (50 years old on average) and covers an area of 236 467 hectares (Gasparini & Tabacchi 2011).

Black pine has been used widely across

Italy because of its typical characteristics of a pioneer species: low mortality, rapid juvenile growth, low incidence of health issues, and the ability to improve both chemical and physical characteristics of the soil. Among the sub-species of *Pinus nigra* Arn., the European black pine (*Pinus nigra* Arn. subsp. *nigra*) was used more commonly on calcareous soils and *Pinus nigra* subsp. *laricio* Maire was preferred on sandstone soils. The main purpose of establishing pine forests in Italy was to protect the soil from erosion, and also to facilitate the natural succession toward mixed forests with a strong component of deciduous species (Cantiani et al. 2010). The commercial value of these pine forests was not a priority.

The most common silvicultural treatments in Europe currently aim at maximizing the stability and facilitating the transition from pure stands to mixed stands with a stronger component of native tree species (Mosandl

& Kessner 1999, Heitz & Hasenauer 2000, Kenk & Guehne 2001, Malcolm et al. 2001, Kint et al. 2006). Black pine was usually planted in pure stands at a density of 2500 trees per hectare with a rotation period of approximately 90 years depending on the site characteristics. During the rotation period multiple thinning usually should be applied to facilitate the transition toward a mixed forest. The average stand age of Italian pine forest is 50 years; consequently, there is still a need for additional research to understand the most effective treatments required to convert these pure pine forests.

On privately owned forests (approximately 47% of the total), the most common treatment is a clear cut on small patches followed by artificial regeneration of native species (e.g., *Acer pseudoplatanus* L., *Acer opalus* Mill., *Quercus cerris* L., *Fraxinus ornus* L., etc.). On public land, larger areas are commonly harvested (e.g., strips, patches) in order to facilitate the natural regeneration of native species.

Thinning is the most effective silvicultural treatment to enhance the ecological value of these stands. Pure pine stands reach canopy closure at an early age; therefore, it is important to conduct pre-commercial thinning at about age 30 followed by additional thinning every 15 years (Cameron 2002, Brüchert & Gardiner 2006). However, multiple thinning is costly and in Italy the necessary treatments have not been applied regularly. In these forests, the most common treatment is thinning from below, which removes only those trees below the main canopy layer that show phytosanitary issues or diseased stems. This trees are mainly dominated.

Cantiani et al. (2010) indicated that black pine can still benefit from late thinning (at the age of 45), thus quickly reaching crown closure when treatments are carried out on the dominant layer. This operation can cause an initial disruption in the crown coverage. Consequently, it is important to evaluate the vigor of the crown and the social status of each tree before proceeding with a silvicultural treatment similar to thinning from above.

Moreover, tree susceptibility to wind and snow damage depends on many physical and ecological factors including: (1) soil characteristics, slope and climate (Copeland et al. 1996, Moore 2000, Quine 2000, Talkkari et al. 2000, Cucchi & Bert 2003, Zeng et al. 2010); (2) species composition, density, diameter distribution, and vertical structure (Valinger et al. 1993, Quine 1995); and (3) the morphological and structural characteristics of individual plants (Coutts 1983, Petty & Swain 1985, Gardiner et al. 1997, Mitchell 2000, Wilson & Oliver 2000, Nicoll et al. 2006, Peltola 2006). The first factor is not influenced by management and cannot be

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Tab. 1 - Plot location and other key information about the pine stands surveyed for this study.

Site	Site code	Elevation (m a.s.l.)	Aspect	Stand age (years)	Tree density (trees ha ⁻¹)	Basal area (m ² ha ⁻¹)	Quadratic mean DBH (cm)	Stand mean height (m)
Monte Amiata	AM	930	NE	40	998	48.3	24.3	22.3
Fonte Archese	AR	750	SW	33	1342	66.75	22.7	15.65
La Baita	BA	880	SW	51	1216	88.6	30.5	20.4
Fonte dei Frassini	FR	1020	W	35	1286	61.2	24.75	15.55
Monte Modina	MO	1050	SE	80	956.5	60	26.7	20.6
Palmoline	PA	1000	NE	55	946.5	61.8	29.45	21.6
Pigelleto	PG	765	NW	67	510	35.5	34.8	24.3
Fonte del Pesce	PS	1210	W	50	896.5	73.35	33	19.8
Monte Pettenaio	PT	1000	NW	35	1377	35.35	18.75	13.05
Lo Sciattolo	SC	900	W	57	1048	61.34	27	23.7

controlled by foresters, the second factor can be controlled only in the long term, the third factor can be very useful in short-term management planning. Indeed, structural characteristics of trees can be a selection criterion on which to base thinning. In the literature, many indicators were used to assess tree stability by morphological and structural characteristics at tree level. The most frequently used indicators are: (a) the height/DBH ratio (slenderness coefficient or taper); (b) the relative depth of the crown; (c) the crown projection; and (d) the crown eccentricity.

The main goal of this study was to investigate a simple and non-invasive method suitable to assess the vigor and vertical stability of pine trees by counting the living whorls along the stem. We also wanted to evaluate whether such method could be particularly effective when selecting the trees that will be preserved from thinning (selective thinning approach).

Materials and methods

Sample description

The target population in this study was represented by all experimental plots held by the Italian Forestry Research Center (CRA-SEL) on black pine plantations in central Italy.

The data set used for this work was composed of 1098 trees. The trees were selected randomly from the CRA-SEL database of experimental black pine plots. The main descriptive parameters of these stands are reported in Tab. 1.

All the stands analyzed were located in central Italy (Fig. 1). With the exception of the MO site, these forests were established on public land since the middle of the past century. The majority of black pine reforestation occurs in central Apennines; consequently, the stands our data come from have an average age of 50 years.

The average density was approximately 2500 trees per hectare following common es-

tablishment treatments. Pre-commercial thinning was not applied. No thinning had been carried out at the time of the survey at the following locations: AR, FR, PT, and SC; at the other locations, a light thinning from below was applied. At the time of the survey, stands presented crown closure with ongoing intra-specific competition.

Tab. 2 provides information on the stands from which the trees were selected, such as number of trees, average diameter at 1.3 m height (DBH), DBH range, average height, and height range. The 1098 sampled trees were classified in three social classes: (a) dominant trees (classes 1 and 2 of Kraft - Pretzsch 2010); (b) co-dominant trees (class 3 of Kraft); and (c) subdominant trees (class 4 and 5 of Kraft).

The sample trees were selected randomly from each stand. A total of 329 dominant trees, 371 co-dominant trees, and 398 subdominant trees were used for the statistical analysis.

Measures and variables

The tree-level measurements used for the models were: (a) diameter at 1.30 m height (DBH); (b) total height (Ht); (c) height of first living whorl (Hc); (d) projection on the ground of 4 orthogonal crown radii (*i.e.*, North, East, South and West – Rc); and (e) number of living whorls from the top of the crown to the lowest living whorl (LWN).

Five variables, relative to the overall stability of the tree, were selected and included: (a) the number of living whorls (LWN); (b) the height/DBH ratio (slenderness coefficient or taper – HD); (c) the relative depth of the crown (CD); (d) the crown projection (CP); (e) the crown eccentricity (largest radius / smallest radius – EC, Brüchert & Gardiner 2006 - Tab. 3).

Exploratory analysis

A principal component analysis (PCA) and a non-parametric correlation analysis (NPC) were used to investigate the relationship between the stability indexes (*e.g.*, LWN, HD, CD), and the significant variables were modeled using the Local Weighted Scatterplot

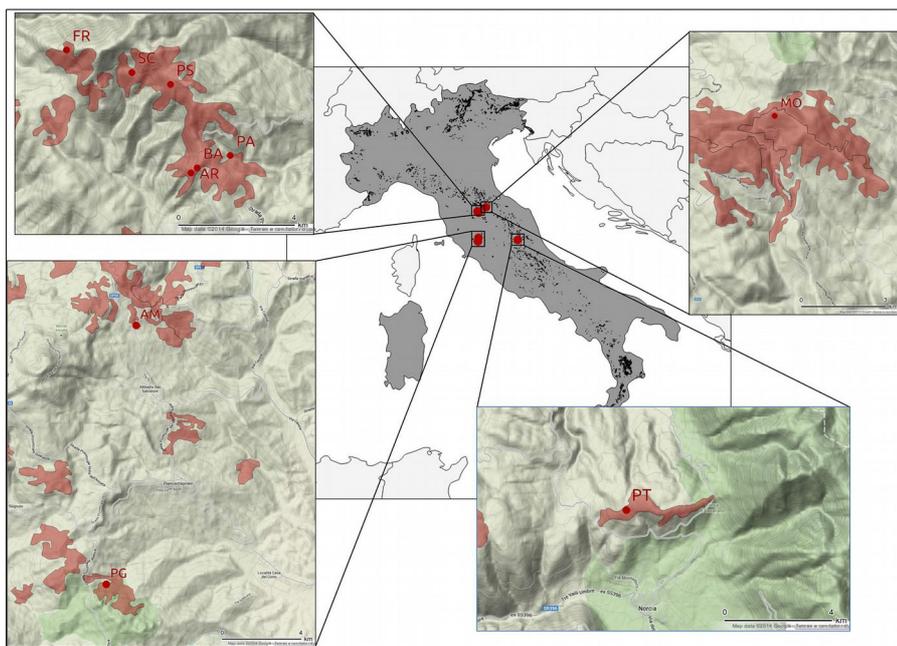


Fig. 1 - Study sites location (red dots) relative to the distribution of black pine stands in Italy (black/red areas).

Smoothing (LOWESS or LOESS - Cleveland 1978, 1981, Cleveland & Devlin 1988).

PCA was used to detect the predictability of the five variables (*i.e.*, LWN, HD, CD, CE, CP). The function `PRINCOMP {STATS}` implemented in the R environment (R Core Team 2013) was applied on the correlation matrix.

The Shapiro-Wilk test (Shapiro & Wilk 1965) was used to investigate whether the selected variables were normally distributed (Tab. 4). Significant departures from normality were observed for most variables, as well as for their logarithmic and root square transformation, and therefore a non-parametric statistical analysis was applied. For this reason, the Spearman's correlation coefficients (ρ - Spearman 1904) were calculated to investigate the relationships between the stability indexes and LWN using the function `RCORR {HMISC}` of the R software (Harrell 2012, R Core Team 2013). Furthermore, the use of a non-parametric test allowed the detection of non-linear relationships among variables.

Crown development is influenced by light availability and by the location of each crown in relation to the surrounding trees. For this reason, the correlation test was performed on the whole dataset and by social class. We used a threshold p-level of 0.001 to determine the significance of the correlation coefficients, also considering the Bonferroni's correction (Dunn 1961).

Modeling

The relationship between HD and LWN was modeled using a non-parametric analysis for two reasons: (a) most variables were not normally distributed (Tab. 4) even after logarithmic or square root transformation; (b) LWN is a discrete variable. Moreover, a parametric approach would be not robust because the relationship between the variables was unknown. A Locally Weighted Scatterplot Smoothing regression (LOWESS) was used to this purpose (Cleveland 1978, 1981, Cleveland & Devlin 1988). The `LOESS {STATS}` function implemented in the R software (R Core Team 2013) was used to build the model. The portion of the dataset for local smoothing was $\alpha = 0.6$ with a weight W_i for each decreasing value, as a function of the distance according to the following equation (eqn. 1):

$$W_i = \left[1 - \left(\frac{D_i}{maxDist} \right)^3 \right]^3$$

where D_i is the distance of the i -th observed value in the α interval; $maxD$ is the distance of the farthest observed point in the α interval.

To set the α level we performed several attempts, thereby the α level was arbitrarily set at 0.6 under two considerations: (a) lower α

Tab. 2 - Descriptive statistics of the sample trees used for this study.

Site code	Number of sample trees	Mean DBH (cm)	DBH range (cm)	Mean height (m)	Height range (m)
AM	70	23.6	14-42	22.3	18.1-27.5
AR	85	22.9	13-34	13.6	10.4-19.1
BA	226	27.5	15-56	19.4	11.4-27.4
FR	59	30.3	18-46	19.2	14.9-21.8
MO	137	28.7	13-51	21.3	15.6-27.7
PA	135	28.3	16-50	21.4	12.2-26.5
PG	20	33.6	26-43	24.5	21.3-26.8
PS	102	23.2	10-38	15.2	10.1-18.8
PT	130	18.4	9-30	14.7	7.3-19.6
SC	134	24.8	13-46	20.7	14.3-29.0
Total	1098	25.6	9-56	18.9	7.3-29.0

Tab. 3 - Descriptive statistics for the following variables: the living whorls number (LWN); the slenderness ratio (HD), the crown depth (CD), the crown projection area (CP) and an eccentricity index of the canopy (EC). (Ht): total height (m); (DBH): diameter at 1.3 m height (m); (Hc): height of first living whorl (m); (Rcmean): arithmetic mean of the crown projection radii (m); (Rcmax): greater of the crown projection radii (m); (Rcmin): smallest of the crown projection radii (m); (CV): coefficient of variation.

Variable	Dimension	Formula	Min	Mean	Median	Max	CV
LWN	count	-	1	16.73	16	39	0.39
HD	adimensional	Ht/DBH	36.07	77.52	75	148.57	0.24
CD	adimensional	1-(Hc/Ht)	0.6289	35.3891	35.4052	60.4545	0.26
CP	m ²	$\pi Rcmean^2$	0.00014	0.379	0.36364	1	0.58
CE	adimensional	Rcmax/Rcmin	0.126	12.788	8.042	128.648	1.19

levels would introduce undulations in the model due to the local distribution of the data; (b) higher α levels would progressively transform the model towards a linear model.

The local regression was performed by the method of weighted least squares. The analytical form of this non-parametric model was provided by the LOWESS algorithm and applied to data by using an *ad-hoc* script in R language (Cleveland 1978, 1981, Cleveland & Devlin 1988, R Core Team 2013). The model was validated by the leave-one-out cross validation using the function `ERRORREST {IPRED}` of the R software (Peters & Hothorn 2009, R Core Team 2013). One observation for each of the 1098 model itera-

tions carried out was excluded from the training dataset. Then, the value estimated by the model was compared for each run with the observed value. In this way, the mean square error (RMSE) and the mean square error percentage (% RMSE) were determined.

Results

Significant departures from the normal distribution were observed using the Shapiro-Wilk test for almost all variables and their most common transformations (Tab. 4).

A good correlation both for LWN-CD and LWN-HD was found using the Spearman test (Tab. 5) both for the whole dataset ($|\rho| >$

Tab. 4 - Results of Shapiro-Wilk normality test (Shapiro & Wilk 1965).

Variable Name	Length	W	p-value
LWN	1098	0.9725	0.00000
CD	1098	0.9974	0.07112
HD	1098	0.9622	0.00000
CE	1028	0.9793	0.00000
CP	1028	0.6896	0.00000
log(LWN)	1098	0.9737	0.00000
log(CD)	1098	0.9966	0.01689
log(HD)	1098	0.8075	0.00000
log(CE)	1028	0.5811	0.00000
log(CP)	1028	0.9869	0.00000
LWN ^{1/2}	1098	0.9948	0.00076
CD ^{1/2}	1098	0.9849	0.00000
HD ^{1/2}	1098	0.9714	0.00000
CE ^{1/2}	1028	0.9466	0.00000
CP ^{1/2}	1028	0.9130	0.00000

Tab. 5 - Results of non-parametric correlation tests (Spearman 1904) between LWN and the other variables with and without stratification by social classes.

Stratum	Statistics	CD	HD	EC	CP
All social classes	ρ	0.6648	-0.6263	-0.2729	0.4770
	p-value	0.00000	0.00000	0.00000	0.00000
	Observations	1098	1098	1028	1028
Dominant trees	ρ	0.5357	-0.3312	-0.2055	-0.0981
	p-value	0.00000	0.00000	0.00026	0.08351
	Observations	329	329	312	312
Co-dominant trees	ρ	0.6032	-0.5226	-0.1733	0.3314
	p-value	0.00000	0.00000	0.00099	0.00000
	Observations	371	371	358	358
Sub-dominant trees	ρ	0.5679	-0.4763	-0.0711	0.3692
	p-value	0.00000	0.00000	0.17932	0.00000
	Observations	398	398	358	358

0.6) and for all the strata according to the various social classes ($|\rho| > 0.45$), except for the dominant layer ($\rho = 0.33$). In both cases, a positive correlation was found between LWN and CD, while a negative correlation was detected between LWN and HD. Furthermore, the correlation coefficient was always highly significant ($p < 0.00001$). Contrastingly, the correlation between LWN and CE was always poor when using either the entire dataset or the social classes ($|\rho| < 0.3$). The correlation coefficient was negative and highly significant (p -value < 0.001). The correlation between LWN and CP was equal to $|\rho| = 0.48$ when using the whole dataset and decreased to $|\rho| < 0.3$ when the sample

was stratified by social class. The correlation was always positive and highly significant (p -value < 0.0001), with the exception of dominant trees.

The PCA carried out showed a clear distinction between three groups of variables (Fig. 2). The first group was composed of CP, CD and LWN, the second group was composed of HD and the third group was composed of CE. The first and the second group accounted for a similar amount of variance, but with opposite effect. The third group, instead, was perpendicular to the other two groups and explained an additional portion of the total variance.

The model obtained for the estimation of

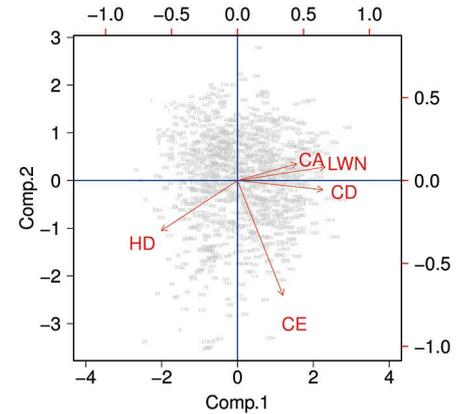


Fig. 2 - Biplot of the PCA.

the slenderness ratio (HD) based on the living whorls number (LWN) is represented in a graphic form in Fig. 3 and Fig. 4. The leave-one-out cross validation of the local regression model resulted in an accuracy of 82% (RMSE = 14.34, RMSE% = 18%).

The general form of the model obtained showed a decreasing trend of HD up to a value of LWN = 23. Then, further increases of LWN values did not determine any further reduction of HD.

Discussion and conclusions

The results of this study indicated a significant relationship between LWN and three out of the four selected stability indexes. As expected, the best correlation was recorded between LWN and CD, indicating that the higher is the number of live whorls, the greater is the depth of the crown. This effect may vary according to the distance between whorls. Site fertility and growing conditions have a direct effect of the distance between whorls (Vanninen et al. 1996), thus site-specific models would increase the predictive ability of LWN.

A significant correlation was also found between LWN and HD. Unlike the previous variables, these two parameters derive from independent measures, which makes LWN a good proxy of the parameter HD. Furthermore, accurate thresholds of stability in terms of HD have been investigated, and therefore LWN may become a valid indicator of individual tree stability.

The relationship between LWN and CP was relatively weak, which is not unexpected. This outcome shows that other factors may affect crown projection. Indeed, crown projection depends strongly on tree density, which was relatively heterogeneous among sites in this study. However, models that include tree density were not a priority, considering that the main goal of the present work was to provide a simple and effective way to assess tree stability in the field.

The relationship between LWN and the ec-

Fig. 3 - Model calibration. Model for estimating the slenderness ratio (HD, red line) based on the living whorls number (LWN). Data used for model calibration are plotted (x).

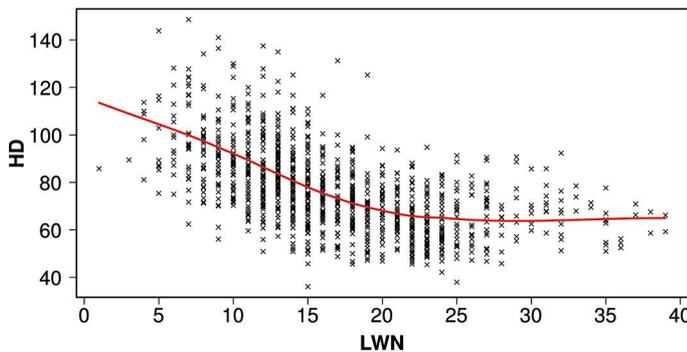
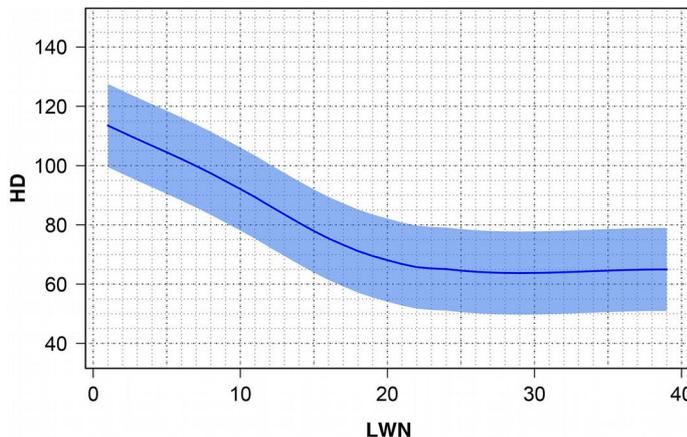


Fig. 4 - Graphical representation of the model obtained (blue line) and its RMSE (light blue area).



centricity of the crown was relatively weak though statistically significant. Moreover, modeling by social class did not improve the ability of predicting HD based on the selected variables. The PCA analysis also indicated that HD, LWN, CD and CP indexes were highly correlated. On one hand, this confirms that HD is a strong indicator of tree stability, as suggested by previous studies (Peltola et al. 2000, Wilson & Oliver 2000, Bachofen & Zingg 2001, Slodcak & Novak 2006, Bianchi et al. 2010, Pretzsch 2010). On the other hand, it demonstrates that LWN and CD can be similarly used to explain the same variation of the parameter HD.

In the scientific literature no studies have been carried out specifically about the mechanical stability of the black pine. Instead, many studies have investigated tree stability of European conifers (Tab. 6), including spruce and fir (*Picea* spp., *Abies alba* Mill.) and *Pinus radiata* D. Don. These studies have indicated that interspecific variability in the HD stability area is relatively low and varies between 75 and 115 (average value = 92.5) for all conifers species combined, while the range is between 85 and 115 (average value = 93.5) for *Pinus* spp. Compared with other conifers, only larch (*Larix decidua* Mill.) had a higher tree stability than black pine (Bouchon 1987). Similar to other conifers, a so-called “HD stability area” is likely between 60 and 90. An HD value above 90 indicates that the pine trees may have stability issues.

In this study, LWN and HD were highly correlated and both showed a strong relationship with tree stability. For all these reasons, our study focused on the relationship between LWN and HD. Furthermore, we demonstrated that there is a constant increase in tree stability for values of LWN up to 23, while for higher values tree stability does not improve even when the number of whorls per tree increases.

Our model provides valid estimates of tree stability for two reasons: (i) the relationship between HD and tree stability indicates a gradual transition around the threshold value from a stable to an unstable tree; (ii) the use of LWN to estimate tree stability indicated that trees can be considered relatively stable for values of LWN higher than 11, and become even more stable for LWN values above 16. This value is conservative and includes the 18% of estimated error. From a forest management perspective, the use of the LWN threshold of 16 may help forest managers to easily select pine trees for thinning. As an example, 50% of trees in our dataset had an LWN value above 16.

In Italy, thinning of black pine forests is usually carried out by selecting trees from below and by using a moderate thinning intensity. In central Italy, the number of trees that can be removed from a stand is re-

Tab. 6 - Reference threshold values of slenderness ratio for the mechanical stability of different conifers.

Species	Slenderness ratio	Country of study and additional notes	Reference
<i>Picea abies</i> (L.) H. Karst	100	Germany	Thomasius et al. (1986)
	90	France - Only for plant from 20 to 30 m of height	Bequey & Riou-Nivert (1987)
	100	Czech republic	Slodcak & Novak (2006)
	100	Scotland	Milne (1995)
	100	Slovakia	Konópka (1999)
<i>Pseudotsuga menziesii</i> Mirb. (Franco)	80	Germany	Abetz (1987)
	75	Netherlands	Faber & Sissingh (1975)
<i>Abies alba</i> Mill.	85-90	Italy	La Marca (2005)
<i>Pinus radiata</i> D. Don.	90-100	Australia - Only for the largest 200 trees ha ⁻¹	Cremer et al. (1982)
	90	Galicia	Castedo-Dorado et al. (2009)
	85	South Africa	Von Gadow & Bredenkamp (1992)
	85	South Africa	Hinze & Wessels (2002)
	115	South Africa	Hinze & Wessels (2002)
<i>Pinus patula</i> Schiede ex Schlechtendal et Chamisso, <i>Pinus elliotii</i> Engelm, <i>Pinus pinaster</i> Aiton, <i>Pinus taeda</i> L.	115	South Africa	Hinze & Wessels (2002)
<i>Pinus sylvestris</i> L.	100	Scotland	Petty & Swain (1985)
<i>Picea sitchensis</i> (Bong.) Carr.	85	United Kingdom	Hamilton & Christie (1971)
Various conifers	100	Canada	Wang et al. (1998)

stricted by law to 40% of the total. For this reason, thinning carried out on high-density stands may not be able to provide a beneficial effect to the overall stand dynamics, as the remaining trees quickly reach crown closure.

According to the most recent findings, thinning in Italian black pine-dominated forests should be more intense (Cantiani et al. 2010). The intensity of a thinning-from-below approach should create gaps large enough to allow sufficient light penetration to the understory. Furthermore, we believe that other forest management practices, such as selective thinning, should be encouraged. Black pine is mainly used to reduce land degradation, and selective thinning should aim at maximizing tree health, so that the overall stability of the stand is improved. Released trees should be those more likely to thrive.

Our model provides a useful and easy-to-use tool for selecting the most vigorous trees within a stand based on the number of whorls per tree. Due to the simplified procedure, using LWN to assess tree stability is less time consuming as compared with the use of HD. Indeed, the calculation of HD requires to measure two variables (DBH and Ht), instead of a simple count of the living whorls. This relatively inexpensive method of estimating tree stability can be particularly important because Italian black pine forests

have limited financial value, but high ecological and hydrological values.

An additional positive outcome of using LWN to assess tree stability is the easy and feasible quality control of thinning practices by competent authority even after the treatment. This method definitely could be used in operational applications in both private and public black pine stands. Furthermore, similar models also could be developed for other species whose whorls can be easily identified and counted.

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