

Technical note

Assessing the mechanical stability of trees in artificial plantations of *Pinus nigra* J. F. Arnold using the LWN tool under different site indexes

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Abstract - In young black pine plantations, the most valuable and interesting thinning scheme is mainly based on the positive selection of dominant and well-shaped trees to be candidates for carbon sequestration, timber production and natural regeneration. The mechanical stability of candidate trees is here a fundamental skill that must be taken into account and the slenderness ratio (HD) is one of the main indicators. HD has been recently proved to be correlated to the living whorl number (LWN) by Cantiani & Chiavetta (2015). In this study, the statistical model was re-calibrated in order to study the influence of soil fertility on the HD - Living whorls number (LWN) relationship. The fertility-balanced models estimated a different LWN threshold. The model for the highest fertility class (Site index 24) estimated 12 LWN (RMSE of 20%). Similarly, a lower value were detected for the other two fertility classes, SI20 and SI16, where 10 LWN were considered enough with an associated RMSE of 16% and 17% respectively. Compared to the general model provided by Cantiani & Chiavetta (11 LWN with 18% of RMSE) the site index approach improved the accuracy and reliability.

Keywords - *Pinus nigra*; living whorl number; tree stability; slenderness ratio; site index; silviculture

Introduction

Artificial tree plantations are among the most fragile and dynamic forest systems. In such forests a variable horizontal and vertical structure may help the development of an adequate mechanical and biological stability. Indeed, the regular planting scheme and the reduced space for roots on the soil (especially for protective forests on thin soils), are among the most important factors of mechanical instability (Coutts 1983). Nowadays, forest management of protective plantations is often carried out following the natural dynamics, modelling gaps and species abundance (Brang et al. 2014, Muscolo et al. 2014). On one hand, thinning is used in young forests to regulate the competition between trees and the amount of solar radiation on the soil. In early stages of young stands (20-40 years), the removal of dominated and deformed trees can increase growth trends of dominants ones and accelerate biological dynamics into the soil (Cantiani et al. 2015). A too high density may cause an excessive competition for natural resources (i.e. drought stresses and reduced growth) and an unbalanced vertical increment, leading trees to be more susceptible to wind storms (Chirici et al. 2015, Dupont et al. 2015).

Trees' mechanical stability is probably the most important skill to be evaluated in any silvicultural practices (e.g. thinning or timber harvesting). Tree density plays a fundamental role in biodiversity conservation and also during the regeneration processes. In this framework, a correct forest management is mandatory to speed up ecological processes and to improve resilience and biodiversity of artificial plantations (Anfodillo et al. 2013, Kerr 1996, Shaw 2006, Tomaiuolo 2010, Valbuena et al. 2008, Yen 2015). It is well known that the health and the mechanical stability of trees is highly related to tree density. While many indicators has been developed to assess biodiversity in forest stands (Becagli et al. 2013, Chiavetta et al. 2016, Latham et al. 1998, Neumann and Starlinger 2001, Pretzsch et al. 2016), just the slenderness ratio (Height/diameter at breast height) has been demonstrated to be a fast and good proxy for mechanical stability of trees (Wang et al. 1998), especially for conifers. Anyway, an innovative method for assessing trees stability in black pine plantations was recently provided by Cantiani & Chiavetta (2015), where the relationships between Living Whorl Number (LWN) and the slenderness ratio (HD) was modelled. The aim was to assess the mechanical stability of pines in artificial pinewoods

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simply by counting the LWN. A total of 1098 trees were randomly extracted from the experimental plots of the Italian Research Centre for Forestry and Wood" (CREA FL) and analysed using a non-parametric approach, the Local Weighted Scatterplot Smoothing (LOWESS). Due to the modelling procedure and the sampling scheme, the final result was considered to be good for almost all the artificial pinewoods along the Italian Apennines chain. The LWN demonstrated to be a simple and informative indicator to estimate the mechanical stability with an average error of 18%. In few words: a black pine with more than 11 living branches (16 taking into account the error of the model) was considered to be very likely to have a HD ratio below 90, that is considered as the threshold for stable black pines.

In this paper an update of the research on HD~LWN relationship is proposed, using the same modelling approach to evaluate the performance of this indicator under different fertility conditions. The novelty of this research consists in a deeper analysis of the data, combining the information derived from the database with the soil's fertility: the Site Index class (SI). To update the same dataset analysed by Cantiani & Chiavetta (2015) with soil characteristics, an overlay procedure in a GIS environment was performed with the management plans of the properties. Afterwards, trees were aggregated following this new approach and a possible influence of soil fertility among different site indexes was investigated. The hypothesis is that with a different vertical growth rate, which is influenced by the SI, the threshold to be used could change.

Materials and Methods

The European black pine (*Pinus nigra* Arnold spp.) is one of the most common species for reforestation programmes on bare or poor soil and in ecologically-demanding situations (Enescu et al. 2016). Despite the differences among provenances, reflected by a different gene pool and consequence of local adaptation in a fragmented natural distribution (Marchi et al. 2016, Nikolic and Tucic 1983, Vidakovic 1974), more subspecies were used during the nursery activities as seed sources (Isajev et al. 2004). Unfortunately, after plantation, the scheduled treatments were rarely applied (e.g. thinning at age 30) (Emer et al. 2011, Lehtimäki and Nurmi 2011) and the management of these plantations is nowadays very challenging. Recently, some black pine plantations in Central Italy were treated with innovative silvicultural treatments (e.g. selective thinning) demonstrating the species to be highly reactive to late-thinning (Cantiani et al. 2010).

The methodology of this paper partially reflects

the one used by Cantiani & Chiavetta (2015). The same tree-level dataset, composed by 1098 trees randomly extracted from the CREA FL database, was used and the same modelling approach (LOWESS) was implemented. This database was compiled between 2000 and 2016 and includes 10 stands distributed across the Apennines Range, between Tuscany and Umbria. The analysed forests are mainly pure black pine stands in public properties around age of 55 years. According to Cantiani and Chiavetta (2015), trees were selected randomly from each stand. A total of 329 dominant trees, 371 co-dominant trees, and 398 sub-dominant trees were used for the statistical analysis. Further data and the spatial distribution of the 10 experimental plot are reported in Cantiani and Chiavetta (2015).

The SI for each of the 10 experimental plot was assessed following the most used and widely applied yield tables for *Pinus nigra* spp. in Italy (Bernetti et al. 1969). Such tables were built considering 87 research plots distributed across the whole Apennines chain and is the reference model for artificial plantations of lario pine (*Pinus nigra* spp. *laricio*) and Austrian pine (*Pinus nigra* spp. *nigra*) in Italy. In these tables three fertility classes were delineated and named "Fertility I", "Fertility II" and "Fertility III", without any information about the regressive model used for the calculation neither a reference value of the dominant height at a defined age (the classical Site Index approach). From this starting point and assuming the SI as the value of the dominant height at age 50 (Nyland 2011), the value for the *Pinus nigra* species in Italy was calculated. Due to the unavailability of the regressive model used by Bernetti et al., the goodness of fit of four widely-used models was tested (linear, logarithmic, power and polynomial). Each model was fitted on tables' data and the one with the highest r^2 was used to calculate the dominant height at age 50 for each research plot, similarly to other researches (Carmean et al. 1989, Hann and Scrivani 1987, Means and Helm 1985, Means and Sabin 1989). Thus, the LOWESS models for each SI were studied, compared among them and to the "complete model" (i.e. with the 1098 trees together). The errors of prediction were calculated to check the quality of the study as well as to test the biased distribution of errors. A leave-one-out cross validation procedure was implemented to calculate BIAS, relative BIAS (RBIAS), root mean square error (RMSE) and root mean square percentage error (RMSPE). Afterwards, a visual comparison was used to assess differences between models and data structure plotting each fertility-balanced LOWESS fit versus the one obtained by Cantiani & Chiavetta (2015), afterwards called "reference model". Finally a non parametric ANOVA was performed to assess differ-

Table 1 - Fitting results on the data of the yield table (Bernetti et al. 1969).

Fertility	Explained proportion of variance (r ²)				Site Index
	Linear	Logarithmic	Power	Polynomial (2 nd order)	
I class	0.9450	0.9956	0.9769	1.0000	24
II class	0.9383	0.9945	0.9694	1.0000	20
III class	0.9405	0.9949	0.9676	1.0000	16

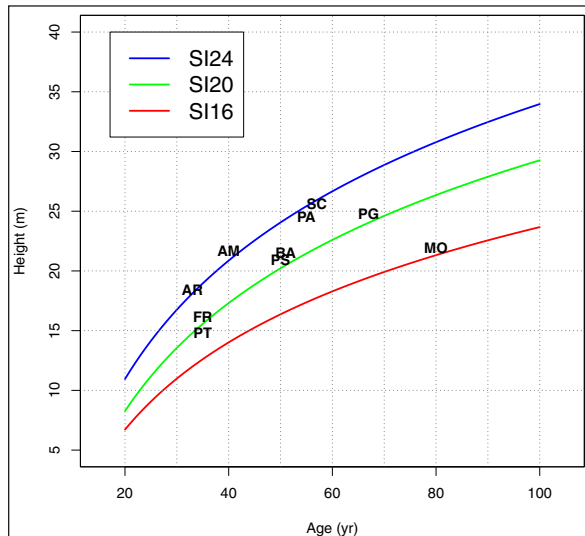


Figure 1 - Site Index classes for *Pinus nigra* spp. in Italy (Bernetti et al. 1969) and study sites.

ences among the average value of LWN for stable trees (HD<=90). Considering the different number of observations for each SI across the database as well as the lack of normality of the distribution, the Wilcoxon Rank sum test (Wilcoxon 1946) was used.

Results

As expected, the second order polynomial curve was detected as the best fitting model for height (Tab.1) with a perfect fit (r²=1) and representing the

Table 3 - Correlation between LWN and HD values.

Dataset	Correlation value (Spearman)	p-value	N. of observations	Av. LWN
Complete	-0.67	<0.0001	1098	18.23
SI24 only	-0.47	<0.0001	411	19.61
SI20 only	-0.70	<0.0001	550	17.86
SI16 only	-0.73	<0.0001	137	15.30

Table 4 - Results of the models. BIAS; RBIAS=Relative BIAS; MAE=Mean absolute error; MAPE=Mean absolute percentage error; RMSE=Root mean square error; RMSPE=Root mean square percentage error; Av.LWN=Average LWN of a stable tree.

Dataset	BIAS	RBIAS	MAE	MAPE	RMSE	RMSPE	Threshold
Refer. model	-0.3232	-0.68%	10.89	14.70%	14.01	18.25%	11
SI24	-0.6677	-4.54%	11.94	15.66%	15.28	19.90%	12
SI20	-0.0609	-2.65%	9.33	13.03%	12.12	15.79%	10
SI16	0.1652	-2.18%	9.36	11.86%	13.09	17.05%	10

same height model (with the same coefficients) used by Bernetti et al. (1969). With this model, the dominant height at age 50 was estimated for each fertility class. For the first class we calculated a site index of 24 meters (SI24), 20 meters (SI20) were calculated for the second class while a dominant height of 16 meters (SI16) was calculated for the third class. In this framework, among the ten research plots, five (411 trees in total) were located into SI24, four in SI20, (550 trees) and only one (137 trees) belonged to the third class, SI16 (Fig.1). The descriptive statistics and the sample plot codes of the updated database are reported in Tab.2. Correlation between LWN and HD were calculated for each strata using the Spearman non-parametric method (Spearman 1987). Compared to the correlation coefficient of the complete dataset, (-0.67), only the first class showed a lower value (-0.47) while the other two were higher (-0.70 for SI20, -0.73 for SI16). However, all the correlations were statistically significant (Tab.3).

Table 2 - Research plots extracted from the CREA FL database (Cantiani & Chiavetta 2015) with the Site Index.

Site	Code	Elevation (m)	Aspect	Age (yr)	Dom.Height (m)	Density (tr.ha ⁻¹)	Basal area (m ²)	Quadratic Mean DBH (cm)	Mean Height (m)	Sample trees	Fertility (Site Index)
Monte Amiata	AM	930	NE	40	21.7	998	48.30	24.3	22.3	70	I (SI24)
Fonte Archese	AR	750	SW	33	18.4	1342	66.75	22.7	15.65	85	I (SI24)
La Baita	BA	880	SW	51	21.5	1216	88.60	30.5	20.4	226	II (SI20)
Fonte dei Frassini	FR	1020	W	35	16.2	1286	61.20	24.75	15.55	59	II (SI20)
Monte Modena	MO	1050	SE	80	21.9	956.5	60.00	26.7	20.6	137	III (SI16)
Palmoline	PA	1000	NE	55	24.6	946.5	61.80	29.45	21.6	135	II (SI20)
Pigelleto	PG	765	NW	67	24.8	510	35.50	34.8	24.3	20	I (SI24)
Fonte del Pesce	PS	1210	W	50	21.0	896.5	73.35	33	19.8	102	I (SI24)
Monte Pettenaio	PT	1000	NW	35	14.8	1377	35.35	18.75	13.05	130	II (SI20)
Lo Scoiattolo	SC	900	W	57	25.7	1048	61.34	27	23.7	134	I (SI24)

The LOWESS models were not biased (RBIAS was lower than $\pm 5\%$ in all cases) and the MAPE ranged between 15.66% of SI24 and 11.86% of SI16, very similarly to the complete model which was 14.70% (Tab.4). The curves' shapes were very similar for SI24 and SI20 and not much different from the reference model. On the contrary, a different form was recognized for SI16. Despite that, the thresholds for stable trees did not differ too much each other and to the reference curve. For SI24 a threshold of 12 LWN (15 considering the error of prediction) was found, and 10 LWN (13 considering the error of prediction) for SI20 and SI16. These latter values differed from the threshold of the reference model, 11 (+5 taking into account the error of the model). A graphical comparison between the four models is provided in Fig.2.

The ANOVA analysis demonstrated that the average value of LWN for stable trees was statistically different for all classes. Considering the whole dataset and without differentiation in SI classes, the average value of LWN for a stable tree ($HD \leq 90$) was 18.23. Clustering the dataset into SI classes, SI24 had an average LWN of 19.61, while for the SI20 and SI16 this value was 17.86 and 15.30 respectively.

Discussion

The analysis demonstrated that even if the general method can be a fair choice for all the conditions, the updated version of the LOWESS model can be more adequate and reliable when a major precision is required and site fertility information are available. In fact the use of the additional information provided by the site index class made the LOWESS model much more accurate for local conditions. The threshold of 11 LWN (+5 in case of inclusion of the error) provided by the reference model demonstrated to be higher for the first class (SI24, with LWN of 12) and more precautionary in case of the second and third classes (SI20 and SI16, with LWN of 10) where a lower value of LWN can assure a reasonable degree of single-tree stability.

Concerning the average number of LWN of stable trees ($HD \leq 90$) statistical differences were detected among fertility classes. Anyway, this aspect has a different meaning from the minimum number to be used as threshold. In fact, the average value does not take into account the "minimum LWN" and is not informative for stability. Indeed, this value is connected more to the shape of the line than to a practical use. In fact, this parameter well describes the last part of the curves (Fig.2) where the values of LWN are higher and the HD is lower. While after 20 LWN the LOWESS curve for SI24 becomes asymptotic to horizontal, this aspect is not present in

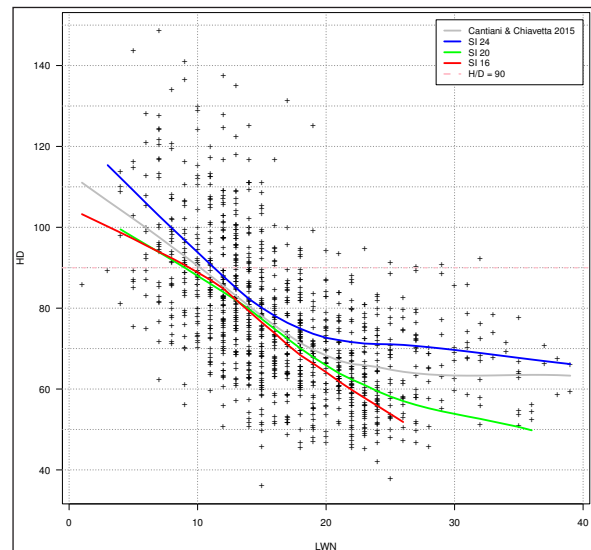


Figure 2 - HD~LWN relationships based on the Site index

case of SI 20 and SI16. The meaning of such shape is that when the site fertility is low, a stable tree with a very high LWN is very rare. For the same reason, the lower height growth rate in lower fertility stands can explain the lower LWN required for stable trees. In addition, this asymptotic trend of the curves is strictly connected to reduced height increment in lower SI classes and has an important biological meaning: the higher the fertility is, the deeper the crown is expected to be. Finally it is also reasonable that shorter trees have a higher stability also with the same HD of taller trees: this is due to the reduced torque for a shorter tree during the application of the same force.

Natural regeneration processes are often desired during the conversion of artificial plantations, such as conifer stands, into more compositionally and structurally complex stands. This aspect currently represents one of the main silvicultural objective in many European countries (Aerts and Honnay 2011, Ciccacese et al. 2012, Sayer et al. 2004, Stanturf et al. 2014). The greater structural and functional stability of trees and forests is here one of the main goals to recover degraded or simplified ecosystems due to direct or indirect human actions (Davis and Slobodkin 2004, Young et al. 2005). Under a practical point of view, this improved model could be proficiently used both in young plantations, when thinning is the main silvicultural treatment, as well as in mature stands, when the aim is to naturally regenerate them or to drive pure stands towards mixed stands (Bravo-Oviedo et al. 2014, Klopčič and Boncina 2012). The selection of stable and mature trees, for example, is fundamental to model the microclimatic variability and gaps dynamics on forests (Muscolo et al. 2014), to obtain the maximum results in terms of wood production, carbon storage and non-wood productions (Cantiani et al. 2015).

In both cases the estimation of stable trees plays a fundamental role. In addition, the LWN indicator can be seen as a double-faced tool: on one side, it is a simple method for selecting trees; on the other side it can be a quick way to control the harvesting activities, i.e. to check if released trees are likely to be stable or not.

The use of the LWN instrument into the Italian context could be easily connected to the Italian regulation. Artificial pinewoods are currently regulated with a very short rotation period (between 40 and 90 years, e.g. Tuscany Regulation) depending on the regional administrations and in relation to the Regional policies (i.e. with the aim to transform them into mixed forests shortly). In this view, the LWN indicator could be successfully used in both cases: selective thinning or selection of candidate trees for natural regeneration. The increased interest in bioenergy from pinewoods (Emer et al. 2011, Lehtimäki and Nurmi 2011) as well as the role of potential substitute for indigenous coniferous species in Central Europe under future climate scenarios (Enescu et al. 2016), currently made the European black pine one of the most interesting species to be used on degraded lands thanks to its ability to tolerate drought stresses especially in case of southern provenances and Mediterranean marginal forest populations (Amodei et al. 2012, Marchi et al. 2015). Additionally, the use of shelterwood system to naturally regenerated this species could become the main field of application of the LWN tool. Similarly the implementation of such modelling approach to other species could increase its potential use. However, a more comprehensive evaluation of trees is always mandatory to take into account further instability factors (e.g. asymmetric crown, deformed stem, etc.).

Conclusions

The general LOWESS model provided by Cantiani & Chiavetta (2015) demonstrated to be a good and stable method also under different soil fertilities. Anyway, in case of lower fertility classes the effect of site index was evident. Specifically site index can contribute to evaluate as stable also trees that with the reference model were classified instable. For this reason, when the Site Index is known and low, the updated thresholds is a more adequate and safer choice when planning and controlling in field activities for thinning or selection of candidate trees.

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