Ruano *et al. Annals of Forest Science* (2023) 80:20
https://doi.org/10.1186/s13595-023-01187-7

Annals of Forest Science

RESEARCH PAPER

Open Access

Improving stem quality assessment based on national forest inventory data: an approach applied to Spanish forests

Antonio Ruano[1,2*], Iciar Alberdi[2], Patricia Adame[2], Daniel Moreno-Fernández[3,4], Alejandro Cantero Amiano[5], Juan Fernández-Golfín[2], Eva Hermoso[2], Laura Hernández[2], Esther Merlo[6], Vicente Sandoval[7] and Isabel Cañellas[2]

Abstract

Key message This paper proposes a methodology that could be considered as a base for a harmonized protocol for stem-quality reporting in Europe while conducting National Forest Inventories, in order to cost-efficiently obtain a visual wood quality proxy. The importance of the variables selected, the limitations identified, and some improvements to the methodology are suggested. Forest areas with better wood quality, which in turn it would be useful for breeding programs, can be easily detected.

Context The establishment of harmonized standards or indicators that allow us to determine the quality of the wood present in a forest prior to its exploitation has long been demanded by the European forestry sector, although agreed methodologies for the evaluation of wood quality in standing trees, which is one of the sector's most urgent requirements, have not, as yet, been implemented.

Aims To develop a protocol that visually characterizes wood quality on standing trees in a cost-effective way for the National Forest Inventory (NFI). After some improvements, it can be considered as a base for a European harmonized protocol.

Methods In this article, we analyze the implementation, in the NFI, of a visual wood-quality assessment methodology in forests of Central Spain based on the different European standards as well as on research papers addressing this issue.

Results The silvicultural practices employed are of the utmost importance to obtain the best wood quality, regardless of the species. Several areas with higher wood quality were identified as well as areas most affected by specific pests in the studied region. The impact of the variables measured (e.g., branchiness, crookedness, maximum branch diameter) is discussed.

Conclusion It is feasible to estimate a proxy for wood quality on standing trees in the NFI. Furthermore, after studying the inventory data provided, several enhancements are proposed, not only to improve wood-quality estimates but also to optimize fieldwork costs. Harmonizing NFIs to assess and map European standing wood quality can be achieved.

Handling editor: Jean-Michel Leban.

*Correspondence:
Antonio Ruano
ruano.antonio@inia.csic.es; antonio.ruano@bc3research.org
Full list of author information is available at the end of the article

Keywords National Forest Inventory, Wood quality, Harmonization, Standing trees, Visual characterization

1 Introduction

Given the importance of wood resources and their by-products in terms of human welfare, it is necessary to quantify forest stocks as well as variables linked to forest dynamics such as regeneration, recruitment (when saplings or young trees surpass a certain threshold growth value), mortality, or harvesting (Vidal et al. 2016a). In this regard, determining stem quality and assortments in European forests is important not only for policymakers and the timber industry, but also for carbon-life-cycle strategies due to the fact that different timber products have different end uses and thus store carbon for different time periods (Bosela et al. 2016).

Fearing that the wood resources would run out and in order to meet the requirement for information on the amount of wood resources, their primary products, and by-products, first forest inventories were implemented at local or regional scale with the aim of providing robust statistics on wood stocks (Breidenbach et al. 2021; Gschwantner et al. 2022; Montes et al. 2005). Sample-based national forest inventories (NFIs) were implemented in the European Nordic countries (Norway, Sweden, and Finland) between 1910 and 1920, due to the importance of forests and wood resources to their economies (Tomppo et al. 2010). Today, many countries carry out sample-based NFIs to assess their natural resources and provide forest indicators to meet the international and national requirements (FAO 2014). According to Nesha et al. (2021), 102 of 236 countries and territories used their NFIs to produce reports for the Food and Agriculture Organization (FAO) of the United Nations Global Forest Resources Assessments (FRA) in 2020.

However, many international conventions, as well as national processes, demand large-scale information on other ecosystem services such as forest structure, carbon sequestration, biodiversity, or wood and non-wood product quantification (Moreno-Fernández et al. 2021, 2020; Alberdi et al. 2017b; Vidal et al. 2016b).

At an international level, there is a growing need for forest indicators in order to support the development and implementation of several environmental policies. However, forest information at a national level, for which NFIs are the main data source, is not always easily comparable between countries (Vidal et al. 2016b). In 2003, the European National Forest Inventory Network was established with the aim of promoting NFIs as comprehensive monitoring systems by harmonizing forest information (Tomppo et al. 2010). The harmonization of NFIs is based on the establishment of reference definitions and functions to transform national data into comparable indicators among countries (Vidal et al. 2016a). There are important ongoing efforts to harmonize the forest information provided by European NFIs, leading to the development of scientific methodologies which allow the validation of results among the different countries (Gschwantner et al. 2019; Vauhkonen et al. 2019; Alberdi et al. 2020, among others).

Forest managers and owners require information on the volume and quality of the wood present in their forests in order to determine the effects of silvicultural and genetic improvement practices and therefore take the most appropriate management decisions with regard to profitability. Moreover, determining the quality of the wood in a productive forest stand prior to its exploitation is also necessary in order to identify the most suitable end use for each log when bucked. Given that specific qualities and requirements must be considered when processing different wood, the quality will partially determine the final use of the felled tree. The estimation of wood quality is important for the sustainable use of forest resources and for the development of optimal planning and conservation activities. Unfortunately, the lack of harmonized surveys for assessing wood quality continues to pose an obstacle in this regard.

Wood properties are determined by studying a series of technical characteristics (e.g., density, stiffness, proportion of juvenile and mature wood, fiber orientation), chemical characteristics (e.g., percentages of cellulose, hemicellulose or lignin, tannin content), and characteristics related to stem growth (e.g., branchiness, distance between knots, stem shape, straightness, and inclination) (Macdonald and Hubert 2002; Larson 1969; Burdon et al. 2004; Lachenbruch et al. 2011). These technical, physical, and chemical characteristics, which are not visible externally, require either collecting wood core samples, felling, or evaluation using non-destructive techniques such as near-infrared spectroscopy, resistance drilling, acoustic-based techniques, or density estimators as proxies for wood quality. These techniques allow many of these characteristics to be estimated without having to resort to intrusive or destructive methods (Wessels et al. 2011; Ruano et al. 2019; Schimleck et al. 2019; Ondrejka et al. 2020). However, these techniques are still at an incipient phase as regards field application and more work is required to validate them and determine their performance and accuracy in standing trees of different sizes and across species (Gallego et al. 2021; Schimleck et al. 2019; Rudnicki et al. 2017; Merlo et al. 2014; Wang et al. 2007). Moreover, due to both economic and temporal limitations, the assessment of wood quality using the abovementioned techniques is not currently feasible for most national-scale surveys (Bosela et al. 2016). Visual morphological characterization of the stem (e.g., branchiness, taper, knottiness, slenderness, straightness, crookedness, forks), which determines the quality of the usable stem on standing trees, is easily measurable in the forest without the need for intrusive or destructive methods. Additionally, the use of this method of characterization reduces field survey costs and therefore may be used as a proxy of wood quality in large-scale surveys (Barger and Ffolliott 1970; Riesco Muñoz et al. 2014; Pretzsch and Rais 2016). Another approach used to evaluate the quality of standing trees based on morphological characterization is by means of photogrammetry or LIDAR techniques (Pyörälä et al. 2019; Kędra et al. 2019; Nguyen et al. 2021).

Although the measurement and application of many variables and definitions associated with forest assessment indicators have been improved and harmonized in the European NFIs (Tomppo et al. 2010; Vidal et al. 2016a), there has been little progress concerning the adequacy of the wood-quality estimation. Bosela et al. (2016) made a first attempt to evaluate the potential of European NFIs to objectively report on stem quality in European forests in a harmonized manner, highlighting the importance of standardizing indicators. They concluded that the majority of European countries have included a direct or indirect approach to evaluate stem quality. However, the heterogeneity of variables measured in the NFIs of different European countries, as well as the different end-use stem quality classifications, hamper attempts to harmonize stem-quality reporting.

In Spain, the First National Forestry Inventory (SNFI-1) was implemented between 1966 and 1975. Since then, two more have been carried out (SNFI-2 1986–1996, SNFI-3 1997–2007) and the fourth cycle is ongoing (SNFI-4) (Alberdi et al. 2017a). A multi-objective inventory, capable of responding to the demand for information on forest biodiversity and conservation, bioeconomy, forest hazards, and disturbances, is currently implemented. Several wood-quality indicators are already assessed during the SNFI fieldwork, although these indicators are not as yet used for subsequent quantification of timber assortments (Alberdi et al. 2017b).

For these reasons, we analyze and propose a methodology in this paper to measure and assess stem quality at national level in the SNFI-4 which entails a compromise between obtaining the desired information and the time and effort required to obtain it by means of a visual classification of the stem. The specific purposes of this paper are (i) to present a field protocol to select key parameters for estimating stem quality in standing trees in the context of the SNFIs (which could be extrapolated to other NFIs), (ii) to apply the new stem quality assessment to a case study in a central Spanish region, and (iii) to discuss the opportunities and limitations identified as well as to suggest improvements prior to the implementation of the protocol in other forest monitoring networks.

2 Materials and methods

2.1 Study area for the case study

To implement and test a new stem-quality protocol, we used data from 4099 plots located in forests of the autonomous community (main administrative unit in Spain) of Castile and Leon (C&L) inventoried during the SNFI-4 (2019–2020). C&L is situated in Northwest Spain covering 94,225 km^2 of which 31.65% corresponds to forests while the remaining land use is mainly agricultural (MAPA 2006). The majority of this region is characterized by a large plateau with an average altitude of 850 m asl and ranging from 116 to 2648 m asl. The plateau is surrounded by three mountain ranges that act as natural borders.

The bioclimatic regions vary from Atlantic (Montane) to Mediterranean (meso-Mediterranean, supra-Mediterranean, and oro-Mediterranean) forests (Aemetblog 2019), resulting in quite diverse forest types from Mediterranean holm Oak forests to Atlantic European beech forests. For commercial purposes and wood industries, the most important forest species are *Pinus pinaster* Ait. (not tapped for resin), *Pinus radiata* D. Don, *Pinus sylvestris* L., *Pinus nigra* J.F. Arnold, *Fagus sylvatica* L., and *Quercus petraea* (Matt.) Liebl. due to the abundance of these species and their historical exploitation. Additionally, at a smaller scale, it was decided to include *Quercus robur* L. and *Castanea sativa* Mill. in this study because of the potential of their wood. For reasons of statistical power and species representativeness, only those tree species represented in at least 20 SNFI plots were considered.

The Köppen-Geiger empirical climate, vegetation-based, classification system (Kottek et al. 2006), and the SNFI-4 plot distribution over the region studied are shown in the Appendix, Fig. 9.

2.2 SNFI and stem-quality protocol

The SNFI consists of permanent plots established systematically in forested areas (Alberdi et al. 2017a) on a 1-km square grid. Each plot is composed of four concentric subplots of 5, 10, 15, and 25 m radii in which trees are measured according to minimum diameter at breast height (dbh) thresholds which are 7.5, 12.5, 22.5, and 42.5 cm, respectively (Alberdi et al. 2016). For each sampled tree, the species is identified and georeferenced, then the dbh and total height are measured, and tree shape and tree vitality status are classified by category (among other variables not related to wood quality).

The stem-quality protocol focuses on commercial species selected by region, specifically on trees with potential commercial uses and they are categorized according to shape and vitality. Within this stem-quality subsample, additional variables (described below) were specifically collected through a field survey simultaneously to the SNFI.

To characterize tree shape, six broad categories are considered based on the stem curvature, tree length, damage, branching, forks, and whether or not the tree has been pollarded. For stem-quality monitoring only, the first two of these categories define the best shapes for potential commercially viable trees. Hence, the trees used in the study were selected according to the following: (i) Shape 1: "the tree has a fusiform bole, the stem is saw timber yielding, clean, straight and is more than 6 m long, the crook is less than 1% of its length, the fiber is not inclined and the dbh is greater than 200 mm"; (ii) Shape 2: "the tree is fusiform, having a saw timber yielding bole of 4 m or more, branches in the upper part". The complete definitions of the tree-shape categories considered in the SNFI are included in the Appendix.

Similarly, the SNFI classifies trees by vitality into six classes according to vigorousness, health status, overage, tree shape, and potential assortments. The first three of these classes are those considered for stem-quality assortment: (i) Class 1: "healthy, vigorous trees, optimally shaped, with no signs of over-aging, able to provide many products of value, not suppressed and with excellent prospects for the future"; (ii) Class 2: "healthy, vigorous, not suppressed trees, with no signs of over-aging although with some form defects and able to provide several products of value"; (iii) Class 3: "trees not totally healthy and vigorous, or somewhat over-aged or suppressed, with quite a few form defects, but able to provide some products of value". The complete definitions of the tree-vitality categories considered in SNFI are included in the Appendix.

In each SNFI plot in which one or more of the target species were present, stem-quality parameters were recorded. This selection is carried out based on the tree species (up to three) with the greatest crown cover. In these plots, up to five trees of the three target species are monitored in the 25-m radius plot, meaning that up to five trees will be selected in monoculture plots while in mixed forests up to fifteen trees could be selected.

The tree selection criteria are the following: (i) measured in the regular SNFI concentric plot design; (ii) dbh $\geq$ 18 cm; (iii) classified under one of the two first categories regarding tree shape defined above; (iv) classified under one of the three first categories of the tree-vitality criteria defined above. Finally, if there are more than five trees of each target species which meet the above criteria, those closest to the center of the plot will be selected.

The following additional measurements are specifically taken for each of the selected trees: (i) two perpendicular measurements of the dbh; (ii) height of the first living branch with a diameter greater than or equal to 1 cm; (iii) height of the first dead branch with a diameter greater than or equal to 1 cm; (iv) height of the base of the crown; (v) presence of spiral grain; (vi) bark thickness (two perpendicular measurements with a bark gauge); (vii) presence of artificial pruning; and (viii) stem leaning.

For *Pinus* species (softwoods), certain variables associated with knottiness, straightness, and presence of and/or damage by specific, harmful, and frequent pests or pathogens are also measured: (i) number of living branches in the first 6 m; (ii) number of dead branches in the first 6 m; (iii) number of whorls in the first 6 m (a whorl is considered if three branches, dead, alive or bumps, are close to each other); (iv) height of the first whorl; (v) diameter of the biggest branch in the first 6 m; (vi) length of the maximum crook (abrupt bend in the merchantable stem) in the first 6 m; (vii) type of crook (simple or multiple); (viii) crown length percentage affected by the pine processionary moth (*Thaumetopoea pityocampa* Denis & Schiffermüller); (ix) crown length percentage affected by the pitch canker disease (*Fusarium circinatum* Nirenberg & O'Donnell); (x) presence of the pitch canker disease (*F. circinatum*) in the stem.

2.3 Tree stem-quality assessment

Once the stem-quality data in each SNFI4 plot had been recorded, a decision tree was defined to assign stem quality to each measured tree.

Firstly, the branchiness and crookedness variables were considered to assess the stem quality of selected trees due to their importance for wood quality. Other variables were subsequently considered to reevaluate this first stem-quality category assigned, such as ovality, lean, presence of spiral grain, maximum branch diameter, or presence of diseases (Fig. 1).

The decision tree for assigning stem quality for each measured tree based on the recorded variables is described below. Note that Quality 1 indicates the best stem quality while Quality 4 denotes the worst stem quality.

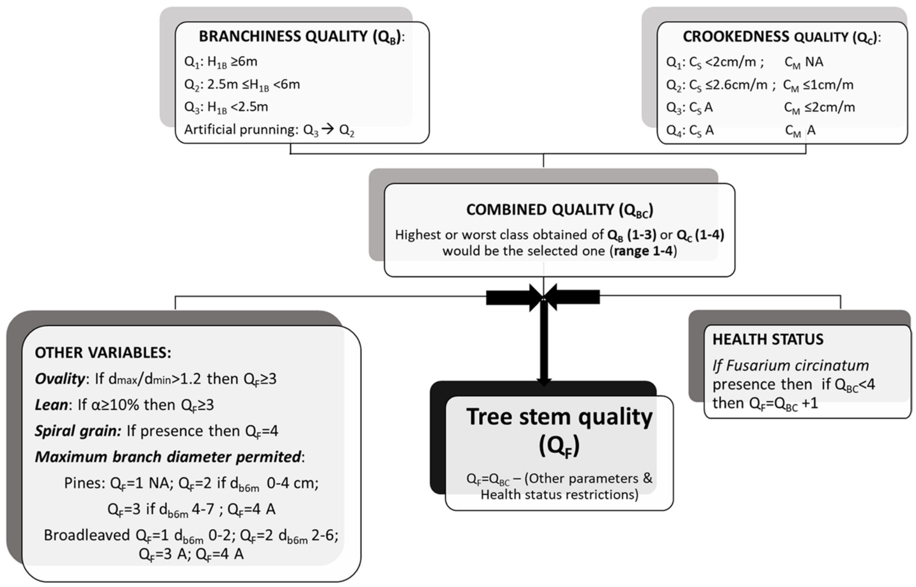

Fig. 1 Synthesized workflow explaining how to obtain the tree stem quality (QF). H1B, height of the first living or dead branch; Cs, Single Crook; CM, Multiple Crook; dmax, maximum diameter at breast height; dmin, minimum diameter at breast height; α, lean angle; db6m, diameter of branches in 6-m height; A, allowed; NA, not allowed

Table 1 Stem-quality classification based on tree branchiness in SNFI-4 plots

Height of the first living or dead branch	Branchiness quality (Q_B)
>6 m	1
2.5–6 m	2
<2.5 m	3

Table 2 Stem-quality classification based on tree crookedness in SNFI-4 plots

Crookedness quality (Q_C)	Single crook	Multiple crooks
1	<2 cm/m	Not allowed
2	≤2.6 cm/m	≤1 cm/m
3	Allowed	≤2 cm/m
4	Allowed	Allowed

2.3.1 Branchiness quality (QB)

To evaluate the tree length free of branches for commercial purposes, three classes were established according to the insertion height of the first living or dead branch.

If branchiness quality is assigned as 3 according to Table 1, but the field team concludes that the tree has been artificially pruned, then it is reclassified as 2. The reason for this is that the knots resulting from pruning are of better quality, if done correctly, than those resulting from self-pruning (Mederski et al. 2019; British Columbia Ministry of forests 1995). If the tree has already been pruned up to a certain height, further pruning up to a greater height could be undertaken in the future.

2.3.2 Crookedness quality (QC)

The second classification regards the tree straightness or crookedness. In this classification, the magnitude of single or multiple crooks is quantified in cm/m, using a modified methodology proposed by Baylot and Vautherin (1991) (Table 2). This variable is only evaluated in softwood species.

2.3.3 Combined branchiness and crookedness quality (QBC)

After assessing branchiness and crookedness, the highest value, i.e., worst class obtained from these two classifications, was selected, that is, the combined branchiness and crookedness quality (Q_{BC}). The Q_{BC} can be modified by other tree features such as ovality, lean, spiral grain, maximum branch diameter, or disease indices. The reevaluation of Q_{BC} gives the final stem quality (Q_F).

2.3.4 Ovality

Ovality is the coefficient obtained after dividing the larger diameter by the smaller one of the two measurements taken perpendicular to each other at breast height. Extreme ovality is related to the eccentric pith and reaction wood, and to a reduction in log quality due to warps produced in the drying process as well as the poorer mechanical properties of this type of wood (Speidel 1957;

Constant et al. 2003). If the ovality index is lower than 1.2 for softwoods, 1.1 for *Populus, Quercus* or *Castanea* species, and 1.15 for *Fagus species* (Speidel 1957; HKS 1969; Jourez et al. 2010; UNE-EN 1316–1:2012; UNE-EN 1316–2:2012), Q_{BC} remains unchanged. For trees with Q_{BC} 1 or 2, if the ovality index is higher than the above values, the Q_{BC} should be changed to 3.

2.3.5 Lean

Lean is considered when the tree bends or slants in a particular direction away from a vertical position. As indicated in Barger and Ffolliott (1970), a lean greater than 10° has a high risk of the presence of reaction wood. Thus, a lean greater than 10° will restrict the Q_{BC} to classes 3 or 4, modifying Q_{BC} 1 or 2 into 3.

2.3.6 Spiral grain

Spiral grain occurs when the longitudinal arrangement of wood-fiber deviation presents an inclination, with a spiral-like pattern circling the trunk. Spiral grain is a highly undesirable characteristic of wood quality. Although important, this variable can change and even shift along the stem during the lifetime of the tree (Skatter and Kucera 1998; Hallingbäck 2010; Watt et al. 2013). Due to the shift in the grain angle that occurs as it grows, we will only attempt to determine whether there is a grain angle greater than 5° in the outer part of the tree rather than measure the actual value (Harris 1984; Hallingbäck 2010). As regards the grain angle, Högberg et al. (2010) identified a strong relationship between the twist in the inner boards and the angle in the outer ring in 36-year-old trees. In order to avoid damaging the tree, if a spiral grain greater than 5° is observed through the bark pattern relative to the longitudinal axis of the stem, the Q_{BC} will be classified as the lowest quality (4).

2.3.7 Maximum branch diameter

The indicator "maximum basal diameter of branches up to 6 m height" was taken into account to classify stem quality according to the Spanish UNE-EN 1927–2:2008 for pines and UNE-EN 1316–1:2012 for beech and oak as quality constraints. For this reason, the maximum branch size in the first 6-m height could directly affect the final quality classification (Q_F) (Table 3).

Table 3 Maximum branch diameter permitted in each class of final stem quality (Q_F)

Species	*Final stem quality (Q_F)*			
	Q_F1	Q_F2	Q_F3	Q_F4
Pines	Not allowed	≤ 4 cm	≤ 7 cm	Allowed
Broadleaved species	≤ 2 cm	≤ 6 cm	Allowed	Allowed

2.3.8 Diseases

The presence of *F. circinatum* on the stem reduces the stem quality by one category of the Q_{BC}. This modification is not applicable in the case of trees with a Q_{BC} rating of 4.

2.3.9 Final stem quality (QF)

Finally, according to the classification scheme shown in Fig. 1, sample trees were classified into 4 possible stem quality categories: plus or premium quality (Q_F1), good quality (Q_F2), average quality (Q_F3) or poor quality (Q_F4), wood suitable only for chipping, firewood, or other uses before trimming.

2.4 Plot stem-quality assessment

To calculate the average stem quality of the plot per species (Q_P), all trees of the target species measured in the regular SNFI survey with a dbh ≥ 18 cm were classified into the two following groups:

- Group A: Trees of tree-vitality class 1, 2, or 3 and tree-shape class 1 or 2.
- Group B: Trees not meeting the criteria of Group A.

First, we calculated the average stem quality of the five selected trees (Q_F) per species in each plot and ascribed this value to the rest of the trees belonging to Group A, while the trees belonging to Group B were ascribed to Q_F 4. Secondly, the quality average weighted by the number of trees within Groups A and B was calculated per species in each plot. Finally, the average Q_F per plot was grouped into a categorical variable (Q_P), as can be seen in Table 4. The synthesized workflow explaining how to obtain the stem quality of the plot (Q_P) per species is presented in Fig. 2.

2.5 Statistical analysis

We used Cohen's kappa statistic and a confusion matrix approach to assess the importance and role of each variable in the definition of stem quality. Cohen's kappa statistic is a chance-corrected method for assessing agreement, rather than association, among raters (Carletta 1996). In other words, it gives an estimation of the proportion of values which are agreements but would not be expected to be agreements by chance if they were independent (DeVellis 2005). Thus, the lower the value of Cohen's kappa statistic, the worse the classification and the more important the variable. The confusion matrix (Kohavi and Provost 1998) contains information on actual and predicted classifications done using the previously explained classification system. The performance of such systems is commonly

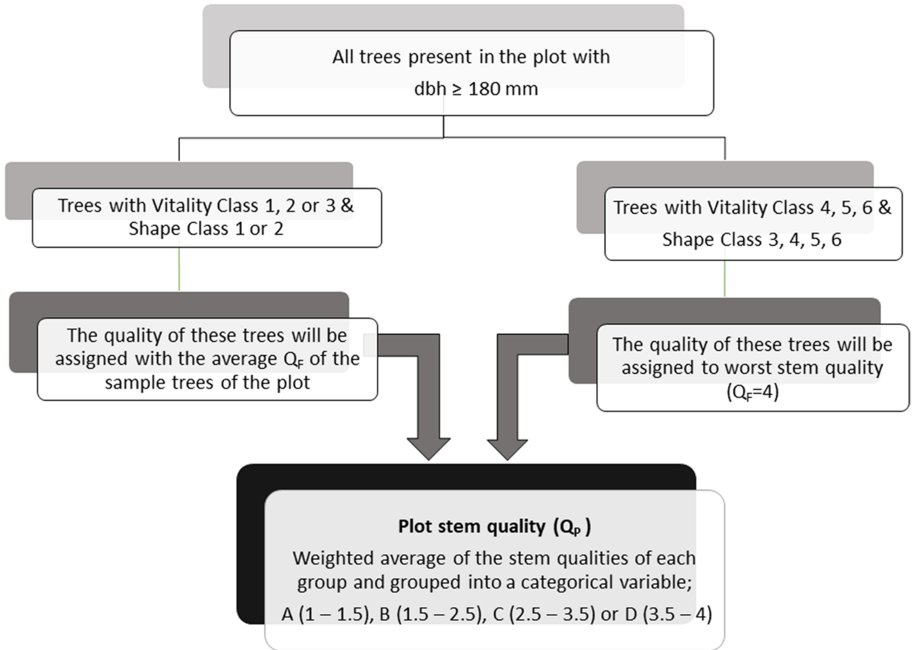

Fig. 2 Synthesized workflow explaining how to obtain the plot stem quality per species. dbh, diameter at breast height; QF, final stem quality; QP, plot stem quality

Table 4 Plot stem quality average per species as derived from the stem quality of all trees present in the plot for each species

Plot stem quality (Q_P)	Average quality (average Q_F)
A	1–1.5
B	1.5–2.5
C	2.5–3.5
D	3.5–4

evaluated using the data in the matrix. In this study, we used both techniques to compare results obtained after eliminating each variable and comparing the results with the true value (results with all the variables).

3 Case-study results

3.1 Analysis of the variables considered for the estimation of stem quality

Out of the 19,819 trees evaluated in the study area according to the selection criteria, 0.32% were *Q. robur*, 1.15% *C. sativa*, 1.41% *P. radiata*, 2.87% *Q. petraea*, 6.11% *F. sylvatica*, 11.22% *P. nigra*, 36.17% *P. sylvestris*, and 40.66% *P. pinaster*. Therefore, 89.46% of the trees evaluated were softwoods.

These trees were sampled in 4099 plots, monoculture plots being the most common while mixed-species plots were marginal (629). Only 70 out of the 629 mixed-species plots contained a mixture of softwood and hardwood trees.

P. sylvestris, *P. pinaster*, and *P. radiata* trees presented the highest average height of the first living branch with values between 6.5 and 6.7 m, followed by *P. nigra* at 5.4 m (Table 5). However, *P. radiata* presented the lowest average dead-branch height of the pines (2.3 m) followed by *P. nigra* (2.6 m). *P. pinaster* and *P. sylvestris* had a similar dead-branch height, 3.9 m and 3.3 m respectively. Among the hardwood species analyzed, *Q. petraea* trees had a first-living-branch height of 4.9 m and a first-dead-branch height of 4.2 m. The first living branch in the *F. sylvatica* trees appeared at around 4.1 m, which was similar to *Q. robur* (4.3 m) and the height of the first dead branch was 4.4 m for *F. sylvatica* and 4.3 m for *Q. robur*. The average height of the first living branch in *C. sativa* was 4.3 m and that of the first dead branch was 3.2 m, this being the lowest of the hardwoods considered.

As regards the variables that consider the percentage of trees with a branchless stem up to a height of 6 m, only 15.3% of *P. pinaster* trees and 12.9% of *P. sylvestris* trees had "clean" stems, and these percentages dropped in the cases of *P. radiata* and *P. nigra* trees down to 5.3% and 4.1% respectively. When evaluating the percentage of trees with living or dead branches at heights below 2.5 m, it was observed that 65.6% of *P. radiata* trees met this criterion, 50.1% for *P. nigra*, 44.9% for *P. sylvestris*, and 29.3% for *P. pinaster*. In the case of the hardwoods,

Table 5 Means and standard deviations (in brackets) and percentage of variables considered for the tree-quality assessment by species

Species	*N* plots	*N* trees	dbh	H1Abranch	H1Dbranch	Crown H	% SG	% Pruned
P. sylvestris	1624	7169	30.1 (9.9)	6.7 (4.0)	3.3 (2.6)	7.6 (4.0)	0.2	16.9
P. nigra	535	2224	26.1 (7.3)	5.4 (2.8)	2.6 (1.5)	6.0 (2.9)	0	32.0
P. pinaster	2021	8058	33.7 (10.1)	6.7 (3.2)	3.9 (2.3)	7.2 (3.3)	0	18.5
P. radiata	64	279	33.8 (12.8)	6.5 (3.6)	2.3 (2.1)	8.3 (4.1)	0	30.1
Q. robur	20	63	37.4 (17.8)	4.3 (1.9)	4.3 (2.2)	6.2 (2.2)	0	0
Q. petraea	147	569	32.6 (14.5)	4.9 (2.8)	4.2 (2.3)	6.9 (2.8)	0.4	0.4
F. sylvatica	298	1210	30.8 (13.0)	4.1 (2.7)	4.4 (2.6)	6.0 (3.0)	0	0.1
C. sativa	74	227	30.4 (14.4)	4.4 (3.2)	3.2 (1.8)	7.1 (3.1)	0.4	7.0

N plots number of plots sampled per species, *N trees* number of trees sampled, *dbh* mean diameter at breast height (cm), *H1Abranch* and *H1Dbranch* mean height of the first living and dead branch, respectively (m), *Crown H* crown height (m), *% SG* percentage of trees with spiral grain (dichotomic variable 0/1), *% Pruned* percentage of artificially pruned trees (dichotomic variable 0/1)

the percentages of *Q. petraea* and *F. sylvatica* trees with branchless stems up to 6 m were almost the same (17.7% and 16.8% respectively), increasing in the case of *Q. robur* (20.6%) and decreasing in the case of *C. sativa* to 6.6%. Regarding the percentage of trees with the presence of branches at heights below 2.5 m, *C. sativa* presented the highest percentages among the hardwoods at 48.9% of the trees, followed by *F. sylvatica* at 39.6%, while *Q. robur* and *Q. petraea* presented very similar data, 33.3% and 32.7% respectively (data not shown).

In the studied region, pruning treatments were commonly found in *P. nigra* (32.0%) and *P. radiata* (30.1%) but were somewhat less frequent in *P. sylvestris* and *P. pinaster* (16.9% and 18.5%, respectively). However, pruning is not carried out up to a height of 6 m, but usually up to a height of approximately 2–3 m. Repeated pruning interventions are less common (Moreno-Fernández et al. 2014). Regarding hardwood species, *C. sativa* was the only species with a significant number of pruned trees (7.0%).

Spiral grain was not observed apart from a few *P. sylvestris, C. sativa* and *Q. petrea* trees. From the data gathered, it would appear that there is little presence of SG in the plots studied.

The specific quality variables measured for the pine species are shown in Tables 6 and 7. *P. pinaster*, together with *P. radiata*, presented the lowest average number of living branches in the first 6 m (5.9 and 6.1 respectively). *P. pinaster* also presented the lowest average number of dead branches (10.2). *P. radiata* presented a high number of dead branches (18.8 on average) as did *P. nigra* with 20.1, this species also displaying the highest average number of living branches up to a height of 6 m (9.6). *P. sylvestris* presented an intermediate average number of living branches (6.5) as well as an average number of dead branches (14.0). However, all these variables exhibit a large intra-specific variability (standard deviation) between all trees studied.

Table 6 Means and standard deviations (in brackets) for the presence and number of branches in softwoods

Species	NbranchesA	NbranchesD	Nwhorls	H1whorl	MaxBranchD
P. sylvestris	6.5 (10.5)	14.0 (12.0)	11.8 (5.6)	1.8 (2.3)	42.4 (36.9)
P. nigra	9.6 (13.4)	20.1 (15.0)	14.0 (5.0)	1.3 (1.2)	35.1 (28.0)
P. pinaster	5.9 (9.9)	10.2 (9.8)	10.8 (5.0)	1.7 (1.8)	35.2 (34.0)
P. radiata	6.1 (10.6)	18.8 (13.9)	10.1 (4.0)	1.2 (1.2)	38.5 (33.1)

NbranchesA number of living branches in the first 6 m, *NbranchesD* number of dead branches in the first 6 m, *Nwhorls* number of whorls visible in the first 6 m, *H1whorl* height of the first whorl, (m), *MaxBranchD* diameter of the thickest branch in the first 6 m (mm)

Table 7 Mean and standard deviations (in brackets) of variables for stem straightness and presence of *Fusarium circinatum* with regard to stem quality in softwoods

Species	% Single crook	% Multiple crooks	Maximum crook	% *F. circinatum* presence
P. sylvestris	93.6	2.9	8.1 (8.4)	0.1
P. nigra	90.4	2.6	7.5 (7.8)	0.3
P. pinaster	80.9	11.4	15.2 (17.8)	8.8
P. radiata	62.7	9.0	8.2 (7.5)	18.6

% Single crook percentage of sampled trees with single crook (dichotomic variable 0/1), *% Multiple crooks* percentage of sampled trees with multiple crooks (dichotomic variable 0/1), *Maximum crook* maximum depth of crook in the first 6 m of the stem (cm), *% F. circinatum presence* percentage of trees with signs of *F. circinatum* in the stem (dichotomic variable 0/1)

The highest average number of whorls up to a height of 6 m was observed in *P. nigra* (14.0), while the number was slightly lower in *P. sylvestris* (11.8). The number was very similar in *P. pinaster* and *P. radiata*, 10.8 and 10.1 respectively. The height of the first whorl in the first 6 m was very similar among the four pines species.

However, as regards the average diameter of the thickest branch in the first 6 m, there were differences, with *P. sylvestris* presenting the largest (42.4 mm), followed by *P. radiata* (38.5 mm), while the smallest diameters corresponded to *P. pinaster* and *P. nigra*, 35.2 mm and 35.1 mm respectively.

The percentage of trees of *P. pinaster* and *P. radiata* with multiple crooks was much higher than that of the other pine species, about 12.5% for both types of crookedness (data not shown). With regard to the maximum crook, the results revealed that *P. pinaster* had the highest average at 15.2 cm although this species also presented a large variability. The average maximum crook for *P. radiata* and *P. sylvestris* was similar, 8.2 cm and 8.1 cm respectively, but high intra-specific variability was also detected. Finally, *P. nigra* presented the lowest average maximum crook at 7.5 cm. The percentage of crooked trees was very high in *P. pinaster*, *P. sylvestris*, and *P. nigra*, about 92–96% of the trees analyzed having some type of crook. However, the large number of trees with a simple crook was due to a misunderstanding of the methodology, since the first range included for the identification of the curvature showed a zero percentage (0–10%). This was corrected for future samplings.

The results for *F. circinatum* presence in the stem revealed that approximately 18.6% of *P. radiata* trees were affected, the percentage falling to 8.8% in the case of *P. pinaster*. The presence was almost negligible for *P. nigra* and *P. sylvestris*, 0.3 and 0.1 respectively.

For pine species, the presence of the processionary moth was also analyzed. Regarding the percentages of tree crown affected per plot, the sites with the highest incidence in *P. nigra* and *P. pinaster* were above 21% and even exceeded 41% in some cases (Fig. 3). However, these data should be interpreted with caution since the data collection was carried out over the whole year; hence, identification of damage among sites may be affected by the month in which they were sampled. In the case of *P. radiata*, the percentage reached 21–30% in northeastern stands, while in the rest of the study area the damage was scarce (0–10%).

3.2 Stem-quality classification

The results from the stem-quality assessment indicated that Final Stem Qualities (Q_F) 2 and 3 are the most common for all the studied species (Fig. 4). The highest proportion of the worst quality (4) was observed in pines, with values ranging between 4 and 19%, whereas the respective percentage of hardwood species did not exceed 1%. It should be noted that more criteria are used to classify stem quality for softwoods than for hardwoods, meaning more restrictions, which could bias the final results. Finally, the highest, Q_F 1, was most prevalent in *P. sylvestris*, *P. pinaster*, *Q. robur*, *Q. petraea*, and *F. sylvatica*, around 10%, while Q_F 1 was rare in *P. nigra*, *P. radiata*, and *C. sativa (<3%)*.

To analyze the relative importance of each variable in the determination of stem quality, the “leaving one

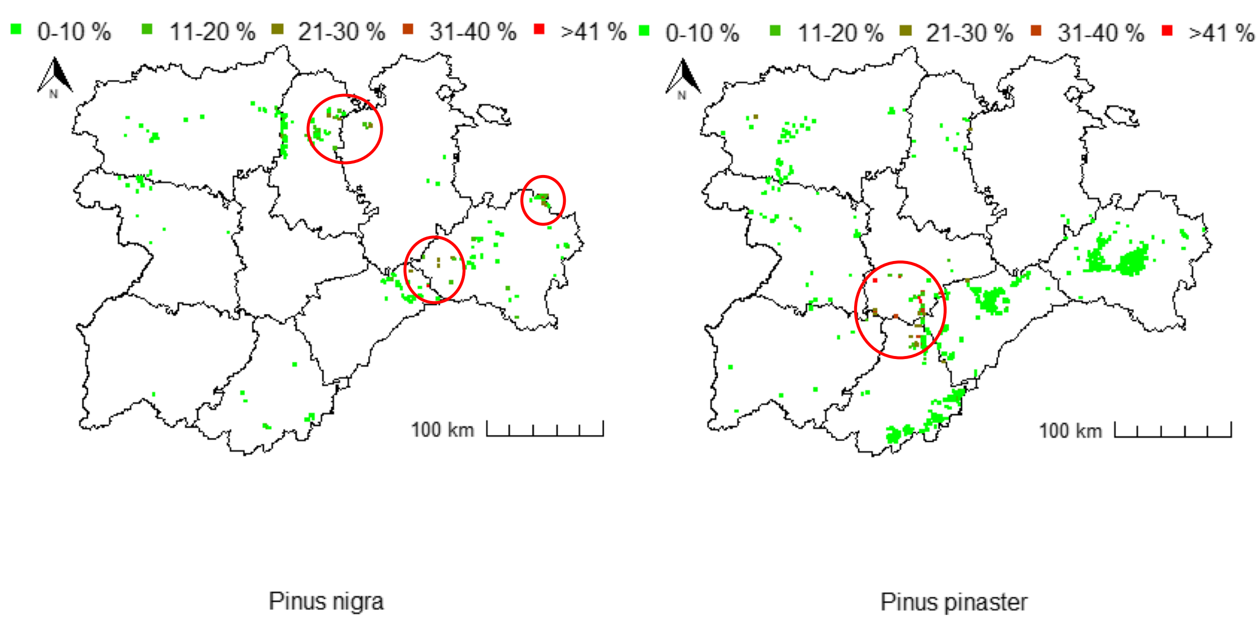

Fig. 3 Regions with high presence of pine processionary moth (red circles) in the *P. nigra* and *P. pinaster* study area according to the average percentage of crown affected

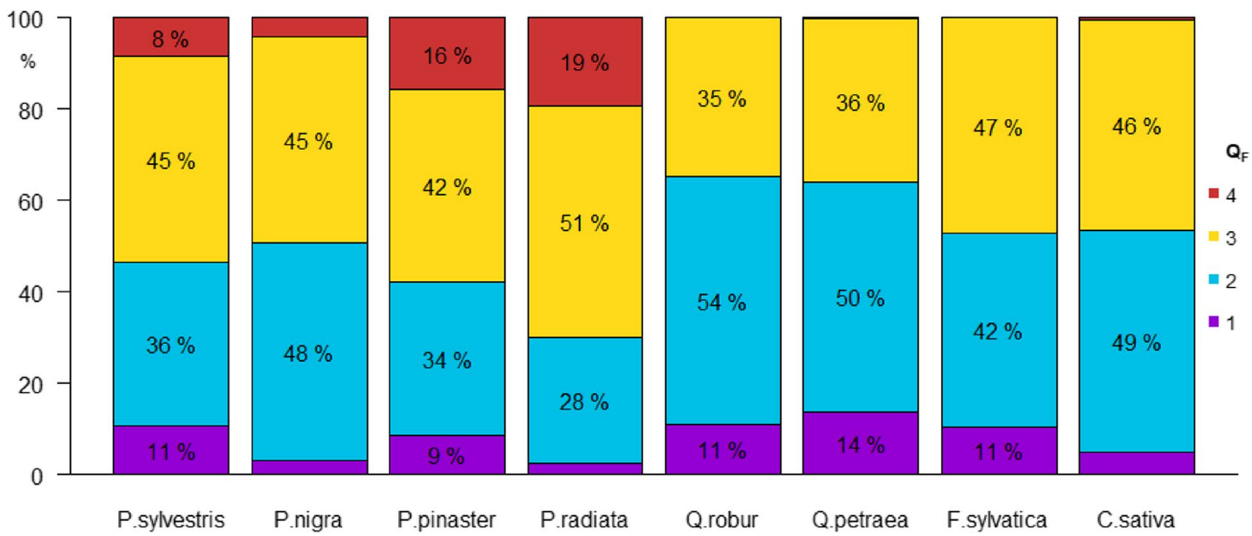

Fig. 4 Estimated final stem quality (QF) percentage per species in the study region. Plus, or premium quality (QF1), good quality (QF2), average quality (QF3), and poor quality wood for chipping, firewood, or other uses after trimming (QF4)

variable out" approach was followed using Cohen's kappa coefficient (Fig. 5) and a confusion matrix (Table 8).

Cohen's kappa statistics revealed that Branchiness is the most important variable (Kappa = 40%) for the estimation of the stem quality using the SNFI data in the studied region. This variable is followed by Crookedness and the Maximum branch diameter with Kappa of around 80% (Fig. 5). In contrast, diseases, lean, spiral grain, ovality, and pruning play only a minor role.

When analyzing the confusion matrices in more detail (Table 8), the weight and role of each variable in stem quality classifications could be shown, as well as the risk of misclassifying the worst stem qualities as higher qualities.

If the Branchiness (Q_B) was not considered, 89% of Q_F 2 and almost 50% of Q_F 3 were misclassified as Q_F 1. If Crookedness (Q_C) was not considered, 2% of the trees belonging to Q_F 2 were classified as the best quality, and for Q_F 3 and Q_F 4 the correct classification was reduced to 86% and 64%, respectively. When the Maximum branch diameter (Q_{MD}) variable was not considered, 8% of the trees of Q_F 3 were misclassified and almost 50% of the trees of Q_F 4 could be misclassified either as Q_F 2 or Q_F 3. Q_F 1 was assumed to not have branches.

The influence of the presence of *Fusarium circinatum* (Q_D) was more evident in trees classified as Q_F 3 which should be Q_F 4 (15%). As regards the other variables, without considering the Lean variable (Q_L), 2% of trees were misclassified, and without the Spiral Grain variable (Q_{SP}) 1% of the trees were misclassified, respectively.

Furthermore, with regard to the confusion matrix, it is important to note that the values are rounded. Due to the large number of sampled trees in the study, if a misclassification was found of less than 99 trees (0.5%), it would not appear in the results. As an example, the variable Q_{SP} presented a 1% misclassification for the worst quality, with more than 147 trees being misclassified as having a better quality. However, since 72 of them were classified as Q_{SP} 2 and 61 as Q_{SP} 3 respectively, when rounded there appears to be an error as 1% was missing, but this was divided between Q_{SP} 2 and Q_{SP} 3.

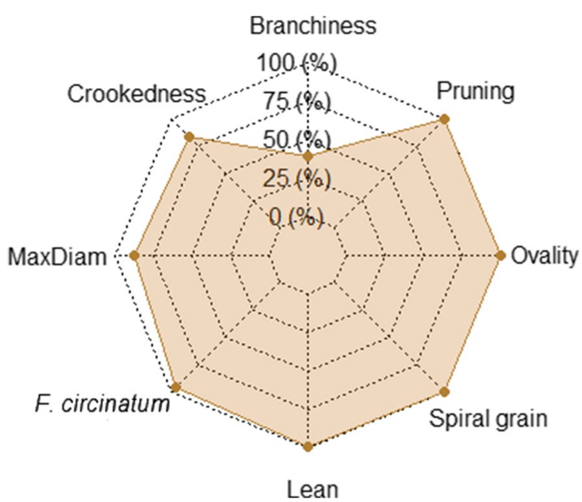

Fig. 5 Cohen's Kappa value obtained when comparing concordances between stem characterization without a given variable

Table 8 Confusion matrix obtained when omitting branchiness (Q_B), crookedness (Q_C), maximum branch diameter (Q_{MD}), presence of *F. circinatum* (Q_D), lean (Q_L), spiral grain (Q_{SP}), ovality (Q_O), and presence of artificial pruning (Q_P) in the determination of the tree stem-quality. Values are in percentage of trees

Q_B	1	2	3	4
1	100	0	0	0
2	89	11	0	0
3	48	6	46	0
4	0	6	2	92

Q_C	1	2	3	4
1	100	0	0	0
2	2	98	0	0
3	3	12	86	0
4	3	17	16	64

Q_{MD}	1	2	3	4
1	100	0	0	0
2	0	100	0	0
3	0	8	92	0
4	0	18	30	52

Q_D	1	2	3	4
1	100	0	0	0
2	1	99	0	0
3	0	3	97	0
4	0	0	15	85

Q_L	1	2	3	4
1	100	0	0	0
2	0	100	0	0
3	0	1	99	0
4	0	0	0	100

Q_{SP}	1	2	3	4
1	100	0	0	0
2	0	100	0	0
3	0	0	100	0
4	0	0	0	99

Q_O	1	2	3	4
1	100	0	0	0
2	0	100	0	0
3	0	0	100	0
4	0	0	0	100

Q_P	1	2	3	4
1	100	0	0	0
2	0	100	0	0
3	0	0	100	0
4	0	0	0	100

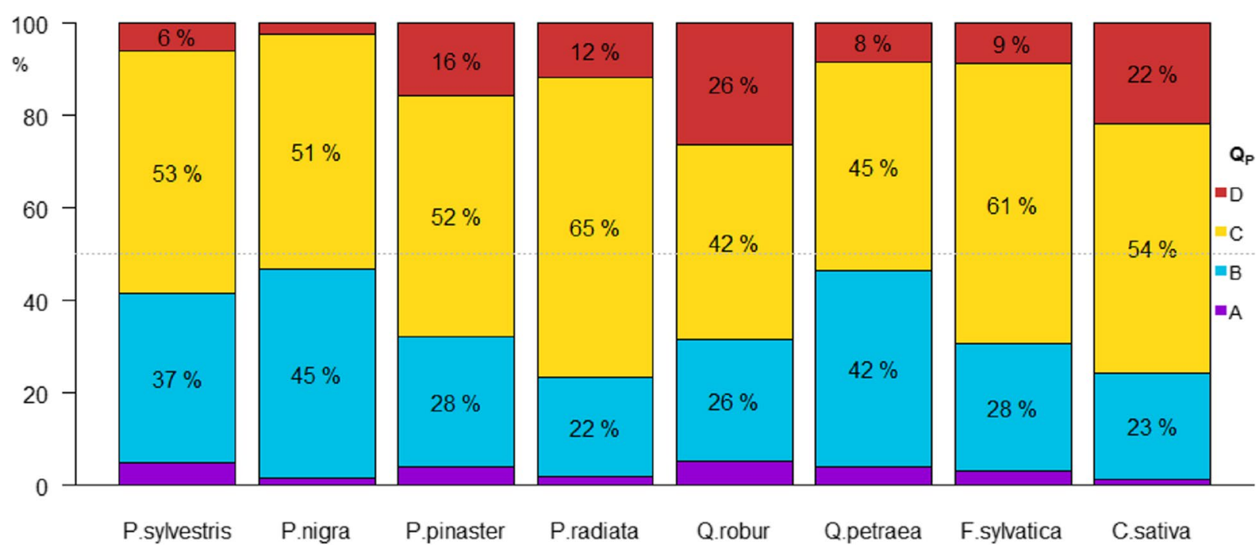

Fig. 6 Percentage of estimated stem quality per plot and species (Q_P) in the study region presented according to Table 4

3.3 Plot stem-quality assessment

The percentages of estimated stem quality per plot and species are shown in Fig. 6. The plot quality (Q_P) for *P. sylvestris* and *P. nigra*, with almost 50% of plots classified into the two best qualities (Q_P A or B), followed a similar pattern to the final quality at tree level (Q_F, Fig. 4). In contrast, the percentages of the two best plot qualities (Q_P A and B) dropped for the rest of the species to 24–32% when extrapolated from tree level to the plot level, except for *Q. petraea* (46%). For the hardwoods studied, it should be noted that there was an important reduction in plot quality due to the number of trees present in the plot that were assigned to Group B.

For illustration, stem-quality distribution maps per species were produced. In the case of *P. pinaster* (Fig. 7), it can be seen that several regions with plots classified as poor stem-quality plots were those where the trees were primarily used for resin harvesting, whereas higher wood quality was found in other areas (4.1% of the plots) which have been managed to obtain higher quality wood for longer periods. For *P. sylvestris* (Fig. 8), the worst-quality and best-quality plots represented 5.90% and 4.83%, respectively. Most of the

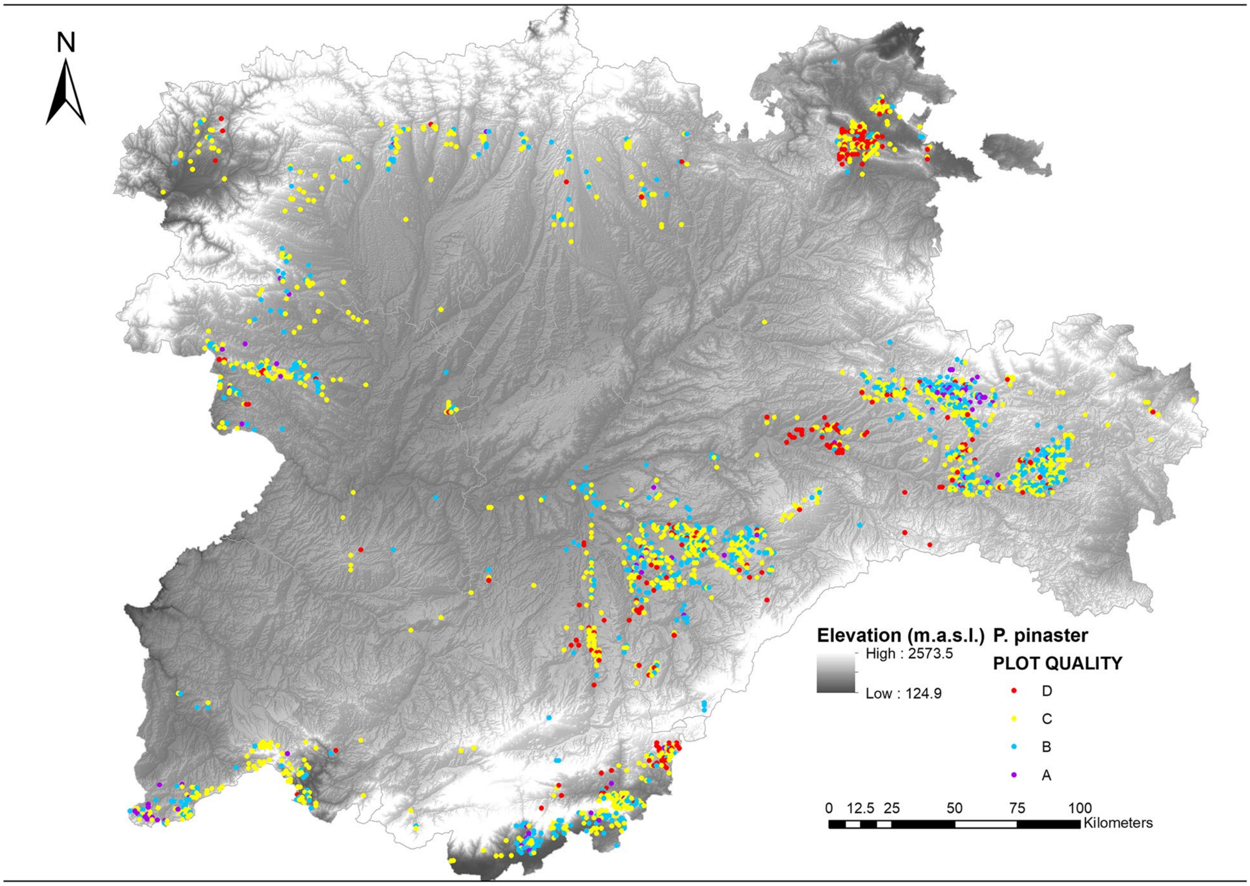

Fig. 7 Distribution of the plot quality for *P. pinaster* SNFI-4 plots in the study area

best-quality plots were located in regions with a long tradition of forest management for timber production.

4 Discussion

4.1 Stem-quality monitoring and assessment in the SNFI

The evaluation of wood quality in forests is a key element for the European forest bioeconomy (European Commission, Directorate-General for Research and Innovation 2018) and bio-circular strategy (European Commission, Directorate-General for Environment 2020). It also provides important data for forest managers and decision-makers. Evaluating wood quality is important not only with regard to the potential value of the standing trees, but also in order to establish adequate forest management prescriptions. Therefore, it is necessary to develop methodologies that can be applied to large-scale inventories (Bosela et al. 2016). With this goal in mind, this article presents an improved methodology to monitor and assess stem quality in Spanish forest stands. In addition, given the transparency and replicability of the protocol and assessment approach presented here, it could provide a step towards a required harmonisation of stem-quality assessment at a European level. Furthermore, an improved methodology to monitor and assess stem quality in Spanish forests has been proposed following the first analysis undertaken in this work.

The case-study results revealed high variability of the variables considered in the stem-quality protocol (Tables 5 and 7). For example, the standard deviations for the number of dead or living branches as well as for the diameter of the thickest branch in the first 6 m of the stem were very high in all studied species. The high variability is understandable because forests considered in this study had different ownerships, site qualities, and management regimes.

The quality indicators Q_B, Q_C, and Q_{MD} are the key variables in the final stem-quality classification, partially due to the decision tree used for the classification. The first two variables (Q_B and $Q_{C)}$ determine the initial quality of the tree, while the rest of the variables considered only limit the classification to the quality assigned by Q_{BC}. In the statistical analysis, diseases, lean, spiral grain, ovality, and pruning variables displayed greater Kappa values, which suggested that

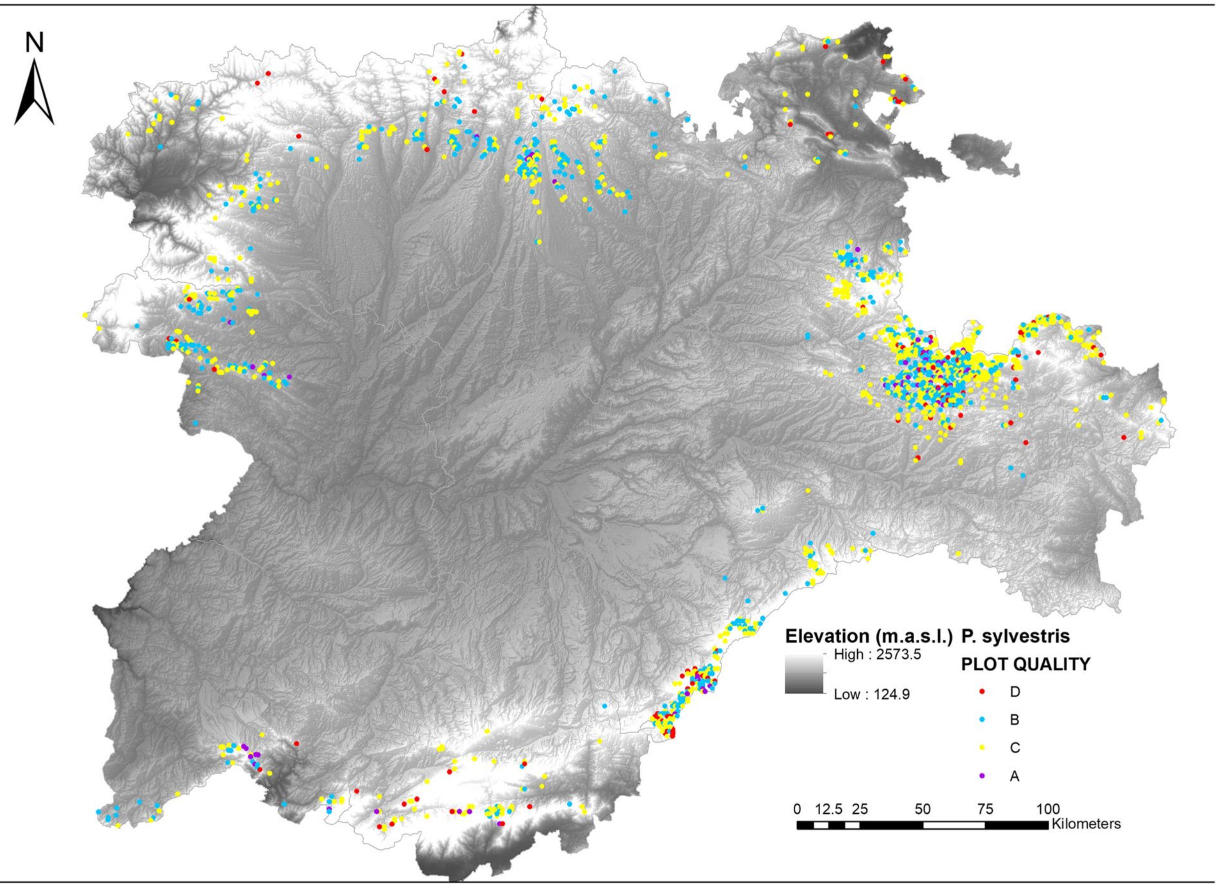

Fig. 8 Distribution of the plot quality for *P. sylvestris* SNFI-4 plots in the study area

these variables have virtually no effect on the classification in terms of the trees misclassified, probably because the influence of these variables is obscured by the effect of other variables that are more restrictive for the quality.

In accordance with the results of this study, the ovality or pruning variables could be omitted in the classification. However, since ovality is estimated from diameter data recorded in NFI, and determining whether artificial pruning is undertaken or not is considered a priority to forest management planning, we considered that it was important to maintain both variables in the classifications. Moreover, it should be noted that the highest pruning percentage was found for *P. nigra*, which is the species with higher percentages of the two best stem qualities (Q_P A and B). In the study region, the low ovality and lean are highly conditioned by the low average slope of most of the forested areas studied. The effect of these variables could be more significant in inventories of forests with steeper slopes or predominant winds (Kellogg and Barber 1981), although Duncker and Spiecker (2005) reported that while the relationship with the slope was not significant, there was a significant relationship with the prevailing wind direction.

The percentage of trees with multiple crooks revealed important differences between species and sites, especially in the case of *P. radiata* and *P. pinaster*, indicating that silvicultural practices or seed/plant selection played an important role for stem straightness.

Mapping the plot quality for *P. pinaster* and *P. sylvestris* clearly showed the forest areas with better quality plots. It is important to note that some studies point to site index (Aguirre et al. 2022; Riesco Muñoz et al. 2014; Watt et al. 2006), long-term forest management (Mäkelä et al. 2010), and the genetic origin of seed/plant material (Jacobs and Davis 2005; Gaspar et al. 2008; Steffenrem et al. 2009; Konofalska et al. 2021) as having a positive influence on plot-quality, although further research should address this matter as we currently lack sufficient data.

In future studies, it would be of interest to verify, if possible, the expected internal quality of trees and whether or not the relationship between internal and external quality is significant. However, this would have to be done individually for each plot, as most of the forested land is privately owned. Additionally, complementing this visual classification with prediction or modeling of tree quality would be interesting if more internal data on the tree could be gathered in future NFIs. For example, Houllier et al. (1995) present a modeling framework for linking forest inventory measurements and wood properties, although it would be necessary to first carefully decide on the best modeling approach (Drew et al. 2022).

4.2 Improving the stem-quality data-collection protocol

After analyzing all the data from the study region, we proposed several modifications to the field protocol as well as the need to add or remove certain variables to ensure the robustness of the stem-quality estimations for the ongoing SNFI in other regions.

The numbers of dead and living branches in the first 6 m of the stem as well as the average diameter were considered variables worth including in the determination of stem quality. For pines, this information could allow the determination of knot area in the circumference of the stem as a proxy of the knot area ratio (KAR) (e.g., SIA 265/1:2009 for round wood) and also provide a proxy for the number of whorls and height of the first whorl in the first 6 m of the stem. Although the two whorl variables would be of real value to estimate knottiness and would be particularly important for the sawmill and the finger-joint industries, given that they enable not only the length of "clear wood" to be determined but also the capacity to obtain it by cutting out the whorl knots, there is a lack of field-data homogeneity regarding the identification of old semi-covered knots. Moreover, even in the case of apparently clear stems, the identification of whorls above a certain height on the tree could be difficult for field operators and lead to further errors and inaccuracy in quality assessment.

Although maximum crook and crook type are mentioned in all of the European standards as important defects for stem quality, they are associated with a certain length of log. Consequently, the straightness evaluation was improved in this study according to Macdonald et al. (2009), who evaluated the crook in terms of the number and length of straight logs in the first 6 m of the tree height (Table 9). Thus, if there is a crook of more than 2 cm/m, the number and length of continuous straight logs that can be obtained from the first 6 m of the tree are evaluated. Additionally, the stem straightness and deviations (lean, sweep, crooked, or straight) were considered, in accordance with the classification proposed by Barger and Ffolliott (1970). A deviation of less than 2 cm/m is not considered a defect. These two new variables related with stem straightness

Table 9 Quality-class assignment for the number and length of straight logs in the first 6 m modified from Macdonald et al. (2009)

Class group	Continuous straight-log length in the first 6 m	Number of logs in the first 6 m
1	≥ 5 m	1
2	≥ 3 m	1
2	Two logs ≥ 2 m	2
3	≥ 2 m	1
4	< 2 m	1

should be measured for all the target species, hardwoods and softwoods.

Another variable of particular interest that was discarded due to the amount of time needed to measure it correctly and the likelihood of inaccurate estimates was the branch insertion angle, which can be an indicator of the size of knot present in structural timber or round timber. The presence of *Viscum album* in the stem was also discarded as it is mainly found beyond the first 6 m of the stem, although under European standards it is considered a reason for rejection from the higher quality classes.

Slenderness, defined as a coefficient between the total height (H) and the diameter at breast height (dbh), was analyzed given the close relationship with wood properties. Slenderness affects both tree stiffness and the properties of sawn timber. Several studies have shown that slenderness, measured prior to felling, can be used to predict the timber stiffness (Roth et al. 2007; Lasserre et al. 2009; Searles 2012) or timber strength (Lindström et al. 2009; Pretzsch and Rais 2016). Slenderness was found to have a positive relationship with stiffness in young loblolly pine (*Pinus taeda* L.) (Roth et al. 2007) associated with higher densities. Tree and stand stability begin to be compromised at slenderness values above 90 because of wind and snow after thinning. It should also be noted, however, that a study of primary forests and uneven-aged forests yielded different results regarding slenderness, pointing to decreasing quality above a certain value (Chivulescu et al. 2019). It is complicated to use this variable in the stem-quality classification method; hence, it was discarded.

As mentioned earlier, knots from artificial pruning have a lesser impact on wood quality (if pruned correctly) than those from natural pruning, although both may be present in the stem. In this regard, the "height of artificial pruning" parameter will provide more useful information than the presence or absence of pruning. Hence, this variable will be substituted in the NFI by "height of artificial pruning."

Aside from the abovementioned variables, new variables will be added in the ongoing NFI to improve stem-quality estimation, such as the taper of the stem in the first 6 m. To evaluate this variable, we propose the use of a laser distance meter, which is able to measure diameters at different heights. The diameter at 1 m as well as at 6 m (or the maximum visible height if less than 6 m) will be measured. The taper will be classified in accordance with the Spanish (UNE-EN 1927–2:2008 for pines).

Furthermore, average density of the wood has been defined as a good estimator of wood quality (eg., Freyburger et al. 2009). A core at 0.5-m height will be extracted using an increment borer, as far as the pith and avoiding reaction wood. The mean density will then be evaluated through gravimetry in the laboratory after drying.

We also propose to include the status of the largest branch in the first 6 m (living, dead with bark, or dead without bark). This data will be used together with the maximum branch diameter in the first 6 m of the stem according to the Spanish and European standards (UNE-EN 1927–2:2008 for pines and UNE-EN 1316–1:2012 and UNE-EN 1316–2:2012 for hardwood species). Additionally, the presence or absence of resin bleeding, as one proxy for resin-pocket presence (Cown et al. 2011), will be considered in the first 6 m of *P. pinaster* stems due to the restrictions in number and size of resin pockets. They are included in most visual timber classification systems, including the European standard. Although resin pockets can also be due to internal checks, knot holes, improper occlusion of broken or pruned branches, or scars.

In the case of *F. sylvatica*, the presence of red heartwood would also be interesting to determine although it is difficult to detect visually on standing trees. Some research into this aspect has been conducted (Wernsdörfer et al. 2005) but we decided to discard it until the use of resistance drilling is implemented in the SNFI.

Clearly, all the abovementioned improvements will make field work more expensive and complicated but will provide a large amount of additional data to improve the estimation of standing-timber quality. However, we should also bear in mind the possible introduction of innovative forest inventory methods, which could optimize and systematize many of these measurements, such as the use of resistance drilling, photogrammetry, or laser scanning.

Finally, in summary, the main variables to be considered in the field survey with the aim of improving the ongoing SNFI stem-quality monitoring and assessment for all species are shown in Table 10.

Table 10 Variables to be measured in the ongoing SNFI

For all species selected	Additional for *Pinus* spp.	Additional for *Eucalyptus* spp.
Tree taper	Number of living branches in the first 6 m	Number of stools (coppiced trees that grow new shoots from the stump) in a coppiced forest in the 5 m radius subplot of the SNFI
Height of the first living branch with a diameter greater than or equal to 2 cm in the first 6 m	Number of dead branches in the first 6 m	Average number of shoots in the mean stool, which should also be located in the 5-m radius subplot
Height of the first dead branch with a diameter greater than or equal to 2 cm in the first 6 m	Average branch diameter in the first 6 m considering both dead and living branches	Percentage of the crown foliar surface damaged by fungal species of the genus *Mycosphaerella* spp. in the five selected trees
Crown base height, if present, in the first 6 m	Diameter of the largest branch in the first 6 m	Percentage of crown damage produced by the eucalyptus weevil (*Gonipterus scutellatus* Gyll.) in the five selected trees
Presence of spiral grain	Phytosanitary status of the largest branch in the first 6 m	
Height of artificial pruning	Crown percentage affected by the pine processionary moth (*T. pityocampa*)	
Type of stem straightness and deviations	Crown percentage affected by the pitch canker disease (*F. circinatum*)	
The length and number of straight-log lengths	Presence of the pitch canker disease (*F. circinatum*) in the stem	
Mean wood density	Presence or absence of resin bleeding in the 6 first m of the *P. pinaster* stems	
Diameter at breast height		
Leaning		
Total height		

5 Conclusion

This paper describes and analyzes a field protocol and assessment approach that allows the stem quality of standing trees to be estimated from morphological variables without the need for specialized tools or materials apart from those which are already needed for standard NFI surveys. Although more information and wider consensus will be needed, it could provide one step towards harmonizing the methodology for monitoring and assessing stem-quality information at European level, thus bridging the current knowledge gap.

On the one hand, the implementation of the methodology proposed in central Spanish forests allowed us to detect some of the forest areas with better wood quality, these areas generally being characterized by stands which have a long history of forest management. Although this methodology could also be of interest in breeding programs, further studies as well as the inclusion of results from other wood quality variables would be necessary.

In this case study, for the selected trees that fulfilled the requirements, the findings indicate that the variables with the greatest impact on visual stem classification are Branchiness, Crookedness, and Maximum branch diameter in the first 6 m of the stem.

After the implementation of the methodology in the case study, certain improvements and potential modifications for new field protocols were identified. The main objectives of these modifications are to optimize the fieldwork costs and to improve the accuracy of stem-quality estimation. Future developments on this work and open discussion with other European countries' experts could lead to an agreement on the basics for the NFIs to assess harmonized standing wood quality.

Appendix

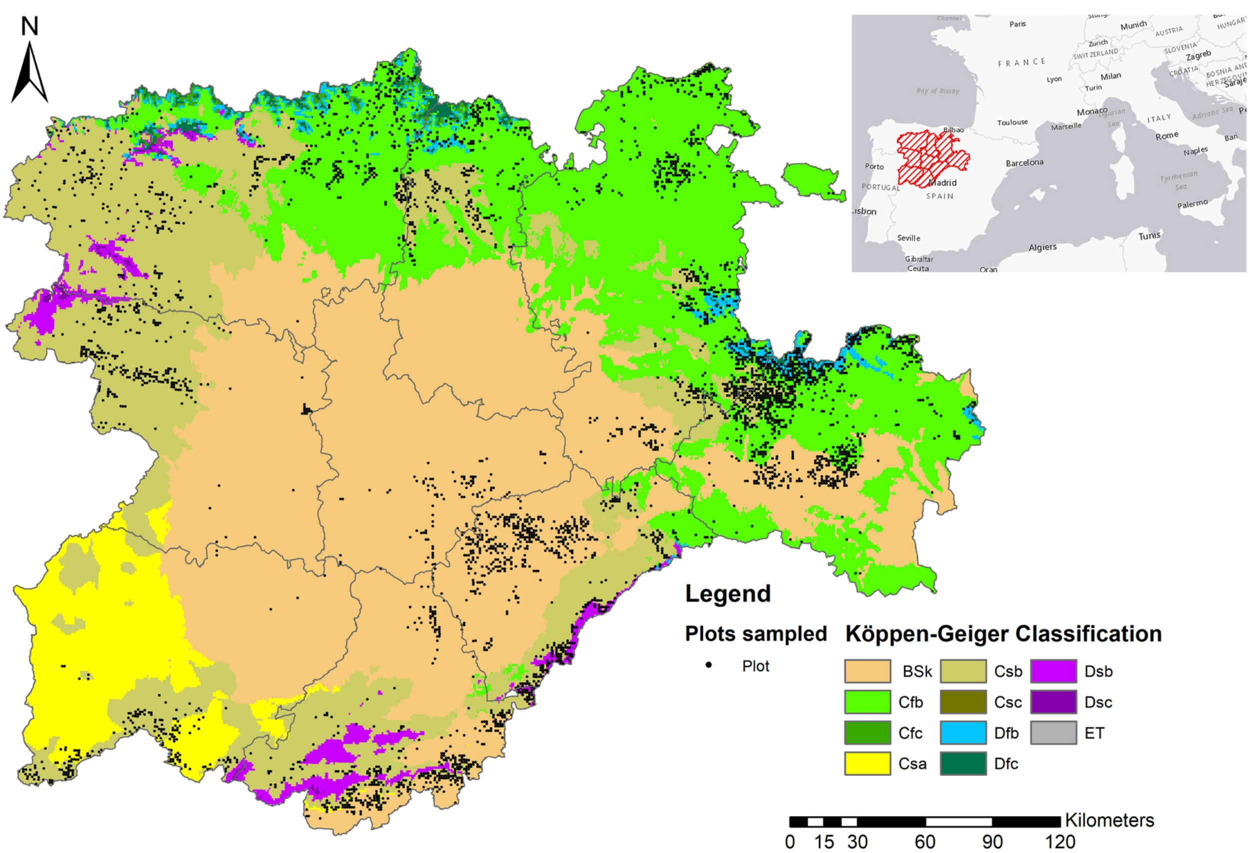

Fig. 9 Köppen-Geiger classification of the study region and SNFI-4 plots sampled. This classification system divides climates into five main climate groups: A (tropical), B (dry), C (temperate), D (continental), and E (polar). The second letter denotes the seasonal precipitation type while the third letter denotes the temperature

Tree-shape classifications according to the SNFI

Six broad categories are considered in the SNFI based on the stem curvature, tree length, damage, fork, branching, and whether or not the tree is pollarded. The tree is then assigned to the Shape that most closely matches one of those listed below:

Shape 1: Tree has a fusiform bole; the stem is timber-yielding, clean, straight, and longer than 6 m; the crook is less than 1% of its length; the fiber is not inclined; and dbh is greater than 200 mm.
Shape 2: Tree is fusiform, having a timber-yielding bole of 4 m or more, branches in the upper part.
Shape 3: Small fusiform trees, in which a trunk diameter of 75 mm is reached at a height below 4 m.
Shape 4: Trees in which the main trunk forks below a height of 4 m.
Shape 5: "Trees in which the stem is full of crooks, damaged or has a lot of branches, so it cannot be classified under forms 1, 2 or 3. This shape also includes trees with a stem height of less than 4 m if they are of different species from those in Shapes 4 and 6"
Shape 6: Topped trees that have had the upper part of the trunk removed as well as the branches close to the point where they are joined to the trunk.

Tree-vitality classifications according to the SNFI

Trees will be divided into six classes, taking into account the health status, the structure with respect to the optimal structure of the species in question, the possibility of supplying more or less goods of superior condition, the exceeding of the mature age (old age), and the situation of the ecosystem. The vitality class assigned will be that which most closely matches those listed below:

Class 1: "healthy, vigorous trees, optimally shaped, with no signs of aging, able to provide many products of value, not suppressed and with excellent prospects for the future".
Class 2: "healthy, vigorous, unsuppressed trees, with no signs of aging but with certain form defects and able to provide several products of value".
Class 3: "trees not totally healthy and vigorous, or somewhat old or suppressed, with quite a few form defects, but able to provide some products of value".
Class 4: "Either a sick, weak or old tree, with numerous shape defects, only capable of providing products of secondary value".
Class 5: "A very sick, weak or old tree, with a very poor shape and which can only provide a few products of little value".
Class 6: "The tree is dead but not yet rotted and still able to provide some exploitable goods".

Acknowledgements
We thank E. Robla for her comments and support.
We are particularly grateful to Adam Collins for editing the manuscript.

Code availability
Not applicable.

Authors' contributions
Conceptualization: AR, IA, DM-F, AC, JF-G, EH, EM, VS, IC. Formal analysis and investigation: AR. Writing—original draft preparation: AR. Writing—review and editing: IA, PA, DM-F, AC, JF-G, EH, LH, EM, VS, IC. Funding acquisition: IC, IA. Resources: VS, IC. Supervision: IA, IC. The authors read and approved the final manuscript.

Funding
Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This work was supported by the Spanish Ministry of Agriculture, Fishing and Food (Encomienda de Gestión.
EG17-042 "Soporte científico a la generación de información Forestal").

Availability of data and materials
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. NFI plot information is freely available at MITECO repository, https://www.miteco.gob.es/en/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare that they have no competing interests.
The funders, aside from limitation budget, had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Author details
[1]Basque Centre for Climate Change, Scientific Campus of the University of the Basque Country, Leioa, Biscay 48940, Spain. [2]Instituto de Ciencias Forestales (ICIFOR-INIA), CSIC, Ctra. La Coruña, Km. 7.5, 28040 Madrid, Spain. [3]Forest Ecology and Restoration Group, Department of Life Science, University of Alcalá, Alcalá de Henares, Madrid 28801, Spain. [4]Department of Natural Systems and Resources, ETSI Montes, Politécnica University of Madrid, Calle de José Antonio Novais, 10, Madrid 28040, Spain. [5]Fundación HAZI Fundazioa, Granja Modelo s/n., Arkaute, Álava 01192, Spain. [6]Madera Plus Calidad Forestal S.L., Parque Tecnológico de Galicia, Avda. de Vigo, 2, San Cibrao das Viñas, Ourense 32900, Spain. [7]Ministerio para la Transición Ecológica y el Reto Demográfico, Plaza San Juan de La Cruz, 10, Madrid 28071, Spain.

Received: 19 November 2022 Accepted: 14 April 2023
Published online: 10 May 2023

References

Aemetblog (2019) Características climáticas y bioclimáticas de la España ibérico-balear. In: Aemetblog. https://aemetblog.es/2019/05/02/carac

teristicas-climaticas-y-bioclimaticas-de-la-espana-iberico-balear/. Accessed 19 Jan 2021
Aguirre A, Moreno-Fernández D, Alberdi I, Hernández L, Adame P, Cañellas I, Montes F (2022) Mapping forest site quality at national level. Forest Ecol Manage 508. https://doi.org/10.1016/j.foreco.2022.120043
Alberdi I, Cañellas I, Bombín RV (2017a) The Spanish National Forest Inventory: history, development, challenges and perspectives. Pesquisa Florestal Bras 37:361–368. https://doi.org/10.4336/2017.pfb.37.91.1337
Alberdi I, Vallejo R, Álvarez-González JG, Condés S, González-Ferreiro E, Guerrero S, Hernández L, Martínez-Jauregui M, Montes F, Oliveira N, Pasalodos-Tato M, Robla E, Ruiz-González AD, Sánchez-González M, Sandoval V, Miguel AS, Sixto H, Cañellas I (2017b) The multi-objective Spanish National Forest Inventory. Forest Syst 26:04. https://doi.org/10.5424/fs/2017262-10577
Alberdi I, Bender S, Riedel T, Avitable V, Boriaud O, Bosela M, Camia A, Cañellas I, Castro Rego F, Fischer C, Freudenschuß A, Fridman J, Gasparini P, Gschwantner T, Guerrero S, Kjartansson BT, Kucera M, Lanz A, Marin G, Mubareka S, Notarangelo M, Nunes L, Pesty B, Pikula T, Redmond J, Rizzo M, Seben V, Snorrason A, Tomter S, Hernández L (2020) Assessing forest availability for wood supply in Europe. Forest Policy Econ. 111:102032. https://doi.org/10.1016/j.forpol.2019.102032
Alberdi I, Hernández L, Condés S, Cañellas I (2016) Spain. In: Vidal C, I Alberdi, Hernández L, Redmond J (eds) National Forest Inventories. Assessment of wood availability and use. Springer, p 749–769. https://doi.org/10.1007/978-3-319-44015-6_41
Barger RL, Ffolliott PF (1970) Evaluating product potential in standing timber. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Dept. of Agriculture, Rocky Mountain Forest and Range Experiment Station, Fort Collins. https://doi.org/10.5962/bhl.title.98801
Baylot J, Vautherin P (1991) Classement des bois ronds résineux. Centre Technique du Bois et l'Ameublement., Paris 94. ISBN-13: 978–2856840016
Bosela M, Redmond J, Kučera M, Marin G, Adolt R, Gschwantner T, Petráš R, Korhonen K, Kuliešis A, Kulbokas G, Fischer C, Lanz A (2016) Stem quality assessment in European National Forest Inventories: an opportunity for harmonised reporting? Ann for Sci 73:635–648. https://doi.org/10.1007/s13595-015-0503-8
Breidenbach J, McRoberts RE, Alberdi I, Anton-Fernandez C, Tomppo E (2021) A century of national forest inventories – informing past, present and future decisions. Forest Ecosyst 8:36. https://doi.org/10.1186/s40663-021-00315-x
British Columbia Ministry of Forests (1995) B. C. Environment. Pruning Guidebook. Forest Practices Code of British Columbia. Forest Service, British Columbia, https://www.for.gov.bc.ca/ftp/hfp/external/!publish/FPC%20archive/old%20web%20site%20contents/fpc/fpcguide/pruning/pruntoc.htm. Accessed 16 Jul 2022
Burdon RD, Kibblewhite RP, Walker JCF, Megraw RA, Evans R, Cown DJ (2004) Juvenile versus mature wood: A new concept, orthogonal to corewood versus outerwood, with special reference to *Pinus radiata* and *Pinus taeda*. Forest Sci 50:399–415. https://doi.org/10.1093/forestscience/50.4.399
Carletta J (1996) Assessing agreement on classification tasks: The kappa statistic. Comput Linguist 22:249–254
Chivulescu S, Leca S, Ciceu A, Pitar D, Apostol B (2019) Predictors of wood quality of trees in primary forests in the Southern Carpathians. Agric Forestry 65(4):101–113. https://doi.org/10.17707/AgricultForest.65.4.09
European Commission, Directorate-General for Research and Innovation (2018) A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment: updated bioeconomy strategy. Publications Office. https://data.europa.eu/doi/10.2777/792130
European Commission, Directorate-General for Environment (2020) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A New Circular Economy Action Plan. For a Cleaner and More Competitive Europe, 98 final; European Commission: Belgium, Brussels, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0098. Accessed 20 Jul 2022
Constant T, Mothe F, Badia MA, Saint-Andre L (2003) How to relate the standing tree shape to internal wood characteristics: proposal of an experimental method applied to poplar trees. Ann for Sci 60:371–378. https://doi.org/10.1051/forest:2003028
Cown DJ, Donaldson LA, Downes GM (2011) A review of resin features in radiata pine. NZ J Forest Sci 41:41–60. ISSN 1179-5395
DeVellis RF (2005) Inter-Rater Reliability, in: Kempf-Leonard, K. (Ed.), Encyclopedia of Social Measurement. Elsevier, New York, 2, p 317–322. https://doi.org/10.1016/B0-12-369398-5/00095-5
Drew DM, Downes GM, Seifert T, Eckes-Shepard A, Achim A (2022) A review of progress and applications in wood quality modelling. Curr Forestry Rep 8:317–332. https://doi.org/10.1007/s40725-022-00171-0
Duncker P, Spiecker H (2005) Compression wood formation and pith eccentricity in *Picea abies L*. depending on selected site-related factors: detection of compression wood by its spectral properties in reflected light. International conference TRACE—Tree rings in Archaeology. Climatol Ecol 3:150–158
FAO (2014) Food and Agriculture Organization of the United Nations. COFO/2014/6.3 Voluntary Guidelines on National Forest Monitoring. Twenty second session Committee on Forestry. Rome, Italy, 23–27 June 2014. http://www.fao.org/3/a-mk174e.pdf. Accessed 12 Apri 2016
Freyburger C, Longuetaud F, Mothe F, Constant T, Leban J-M (2009) Measuring wood density by means of X-ray computer tomography. Ann For Sci 66:804. https://doi.org/10.1051/forest/2009071
Gallego A, Ripoll MA, Timbolmas C, Rescalvo F, Suarez E, Valverde I, Rodríguez M, Navarro FB, Merlo E (2021) Modulus of elasticity of I-214 young poplar wood from standing trees to sawn timber: influence of the age and stand density. Eur J Wood Wood Products 79:1225–1239. https://doi.org/10.1007/s00107-021-01675-5
Gaspar MJ, Louzada JL, Aguiar A, Almeida MH (2008) Genetic correlations between wood quality traits of *Pinus pinaster* Ait. Ann for Sci 65:703–703. https://doi.org/10.1051/forest:2008054
Gschwantner T, Alberdi I, Balázs A, Bauwens S, Bender S, Borota D, Bosela M, Bouriaud O, Cañellas I, Donis J, Freudenschuß A, Hervé J-C, Hladnik D, Jansons J, Kolozs L, Korhonen KT, Kucera M, Kulbokas G, Kuliešis A, Lanz A, Lejeune P, Lind T, Marin G, Morneau F, Nagy D, Nord-Larsen T, Nunes L, Pantić D, Paulo JA, Pikula T, Redmond J, Rego FC, Riedel T, Saint-André L, Šebeň V, Sims A, Skudnik M, Solti G, Tomter SM, Twomey M, Westerlund B, Zell J (2019) Harmonisation of stem volume estimates in European National Forest Inventories. Ann for Sci 76:24. https://doi.org/10.1007/s13595-019-0800-8
Gschwantner T, Alberdi I, Bauwens S, Bender S, Dragan Borota D, Bosela M, Bouriaud O, Breidenbach J, Donis J, Fischer C, Gasparini P, Heffernan L, Hervé JC, Kolozs L, Korhonen KT, Kovácsevics P, Kučera M, Kulbokas G, Kuliešis A, Lanz A, Lejeune P, Lind T, Marin G, Morneau F, Nord-Larsen T, Nunes L, Pantić D, Redmond J, Rego FC, Riedel T, Šebeň V, Sims A, Skudnik M, Tomter SM (2022) Growing stock monitoring by European National Forest Inventories: Historical origins, current methods and harmonisation. Forest Ecol Manage 505:119868. https://doi.org/10.1016/j.foreco.2021.119868
Hallingbäck H. (2010) Genetic improvement of shape stability in Norway Spruce and Scots Pine sawn timber. Doctoral Thesis, Swedish University of Agricultural Sciences, Uppsala, p 1–52
Harris JM (1984) Non-destructive assessment of spiral grain in standing trees. NZ J Forest Sci 14(3):395–399
HKS (1969) Verordnung über gesetzliche Handelsklassen für Rohholz, Vom 31.07.1969. Bundesgesetzblatt, Teil 1, Bonn. https://www.bgbl.de/xaver/bgbl/start.xav?start=//*%5B@attr_id=%27bgbl169s1075.pdf%27%5D#__bgbl__%2F%2F*%5B%40attr_id%3D%27bgbl169s1075.pdf%27%5D__1683124651874. Accessed 20 July 2022
Högberg K-A, Persson B, Hallingbäck HR, Jansson G (2010) Relationships between early assessments of stem and branch properties and sawn timber traits in a *Pinus sylvestris* progeny trial. Scand J for Res 25(5):421–431. https://doi.org/10.1080/02827581.2010.509330
Houllier F, Leban J-M, Colin F (1995) Linking growth modelling to timber quality assessment for Norway spruce. For Ecol Manage 74(1–3):91–102. https://doi.org/10.1016/0378-1127(94)03510-4
Jacobs DF, Davis AS (2005) Genetic Considerations in the Operational Production of Hardwood Nursery Stock in the Eastern United States. Native Plants J 6:4–13. https://doi.org/10.2979/NPJ.2005.6.1.4
Jourez B, de Wauters P, Bienfait O (2010) Le classement des bois feuillus sur pied. Silva Belgica 117: p 1–12. https://orbi.uliege.be/bitstream/2268/95733/1/classement%20bois-Silva%204%20BD-5.pdf. Accessed 20 Jul 2022
Kędra K, Barbeito I, Dassot M, Vallet P, Gazda A (2019) Single-image photogrammetry for deriving tree architectural traits in mature forest stands: a

comparison with terrestrial laser scanning. Ann for Sci 76:1–13. https://doi.org/10.1007/s13595-018-0783-x
Kellogg RM, Barber FJ (1981) Stem eccentricity in coastal western hemlock. Can J for Res 11(3):715–718. https://doi.org/10.1139/x81-099
Kohavi R, Provost F (1998) Glossary of terms. Machine learning—special issue on applications of machine learning and the knowledge discovery process. Mach Learn 30:271–274. https://doi.org/10.1023/A:1017181826899
Konofalska E, Kozakiewicz P, Buraczyk W, Szeligowski H, Lachowicz H (2021) The technical quality of the wood of scots pine (Pinus sylvestris L.) of diverse genetic origin. Forests 12:619. https://doi.org/10.3390/f12050619
Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130
Lachenbruch B, Moore JR, Evans R (2011) Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence. In: Meinzer FC, Lachenbruch B, Dawson TE (eds) Size- and age-related changes in tree structure and function. Springer, Berlin, pp 121–164. https://doi.org/10.1007/978-94-007-1242-3_5
Larson PR (1969) Wood formation and the concept of wood quality. Yale University, School of Forestry, New Haven, CT, Bulletin no. 74: 1–54. https://www.fs.usda.gov/nrs/pubs/other/1969/nc_1969_larson_001.pdf. Accessed 22 Jul 2022
Lasserre J-P, Mason EG, Watt MS, Moore JR (2009) Influence of initial planting spacing and genotype on microfibril angle, wood density, fibre properties and modulus of elasticity in Pinus radiata D Don Corewood. Forest Ecol Manage 258:1924–1931. https://doi.org/10.1016/j.foreco.2009.07.028
Lindström H, Reale M, Grekin M (2009) Using non-destructive testing to assess modulus of elasticity of *Pinus sylvestris* trees. Scand J for Res 24:247–257. https://doi.org/10.1080/02827580902758869
Macdonald E, Hubert J (2002) A review of the effects of silviculture on timber quality of Sitka spruce. Forestry: Int J Forest Res 75;(2):107–138. https://doi.org/10.1093/forestry/75.2.107
Macdonald E, Mochan S, Connolly T (2009) Validation of a stem straightness scoring system for Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Forestry: Int J Forest Res 82:419–429. https://doi.org/10.1093/forestry/cpp011
Mäkelä A, Grace Deckmyn G, Kantola A, Campioli M (2010) Simulating wood quality in forest management models. Forest Syst 19:48–68. https://doi.org/10.5424/fs/201019S-9314
MAPA (Ministerio de Agricultura Pesca y Alimentación) (2006) Mapa Forestal de España (MFE50). https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/mfe50.aspx. Accessed 22 Jul 2022
Mederski PS, Szczawiński D, Giefing DF, Naparty K, Brunka M (2019) Knot soundness and occlusion time after the artificial pruning of oak. For Res Pap 80(1):5–12. https://doi.org/10.2478/frp-2019-0001
Merlo E, Álvarez-González JG, Santaclara O, Riesco G (2014) Modelling modulus of elasticity of Pinus pinaster Ait. in northwestern Spain with standing tree acoustic measurements, tree, stand and site variables. Forest Syst 23(1):153–166. https://doi.org/10.5424/fs/2014231-04706
Montes F, Sánchez M, del Río M, Cañellas I (2005) Using historic management records to characterize the effects of management on the structural diversity of forests. For Ecol Manage 207:279–293. https://doi.org/10.1016/j.foreco.2004.10.031
Moreno-Fernández D, Sánchez-González M, Álvarez-González JG, Hevia A, Majada JP, Cañellas I, Gea-Izquierdo G (2014) Response to the interaction of thinning and pruning of pine species in Mediterranean mountains. Eur J Forest Res 133:833–843. https://doi.org/10.1007/s10342-014-0800-z
Moreno-Fernández D, Hernández L, Cañellas I, Adame P, Alberdi I (2020) Analyzing the dynamics of the deadwood carbon pool in Spain through the European level i monitoring programme. Forest Ecol Manage 463:118020. https://doi.org/10.1016/j.foreco.2020.118020
Moreno-Fernández D, Cañellas I, Alberdi I, Montes F (2021) Improved stand structure characterization from nested plot designs in the Spanish National Forest Inventory. Forestry: Int J Forest Res 94(2):244–257. https://doi.org/10.1093/forestry/cpaa031
Nesha MK, Herold M, De Sy V, Duchelle AE, Martius C, Branthomme A, Garzuglia M, Jonsson O, Pekkarinen A (2021) An assessment of data sources, data quality and changes in national forest monitoring capacities in the Global Forest Resources Assessment 2005–2020. Environ Res Lett 16(5):054029. https://doi.org/10.1088/1748-9326/abd81b
Nguyen V-T, Constant T, Colin F (2021) An innovative and automated method for characterizing wood defects on trunk surfaces using high-density 3D terrestrial LiDAR data. Ann For Sci 78:1–18. https://doi.org/10.1007/s13595-020-01022-3
Ondrejka V, Gergeľ T, Bucha T, Pástor M (2020) Innovative methods of non-destructive evaluation of log quality. Central Eur For J 66:1–11. https://doi.org/10.2478/forj-2020-0021
Pretzsch H, Rais A (2016) Wood quality in complex forests versus even-aged monocultures: review and perspectives. Wood Sci Technol 50:845–880. https://doi.org/10.1007/s00226-016-0827-z
Pyörälä J, Saarinen N, Kankare V, Coops NC, Liang X, Wang Y, Holopainen M, Hyyppä J, Vastaranta M (2019) Variability of wood properties using airborne and terrestrial laser scanning. Remote Sens Environ 235:111474. https://doi.org/10.1016/j.rse.2019.111474
Riesco Muñoz G, Santaclara Estévez Ó, Álvarez González JG, Merlo Sánchez E (2014) Influence of provenance, silvicultural regime and tree shape on the quality of maritime pine (*Pinus pinaster*) timber. Eur J Forest Res 133:623–630. https://doi.org/10.1007/s10342-014-0790-x
Roth BE, Li X, Huber DA, Peter GF (2007) Effects of management intensity, genetics and planting density on wood stiffness in a plantation of juvenile loblolly pine in the southeastern USA. For Ecol Manage 246:155–162. https://doi.org/10.1016/j.foreco.2007.03.028
Ruano A, Zitek A, Hinterstoisser B, Hermoso E (2019) NIR hyperspectral imaging (NIR-HI) and µXRD for determination of the transition between juvenile and mature wood of *Pinus sylvestris* L. Holzforschung 73:621–627. https://doi.org/10.1515/hf-2018-0186
Rudnicki M, Wang X, Ross RJ, Allison RB, Perzynski K (2017) Measuring wood quality in standing trees: a review. General technical report FPL-GTR-248, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison. 248, p 13. https://www.fpl.fs.usda.gov/documnts/fplgtr/fpl_gtr248.pdf. Accessed 20 Jul 2022
Schimleck L, Dahlen J, Apiolaza LA, Downes G, Emms G, Evans R, Moore J, Pâques L, Van den Bulcke J, Wang X (2019) Non-destructive evaluation techniques and what they tell us about wood property variation. Forests 10(9):1–50. https://doi.org/10.3390/f10090728
Searles GJ (2012) Acoustic segregation and structural timber production. PhD thesis, Edinburgh Napier University, Edinburgh, UK https://www.napier.ac.uk/~/media/worktribe/output-190958/searlesacousticsegregationandstructuraltimberproductionpdf.pdf. Accessed 20 Jul 2022
SIA 265/1:2009 Schweizerischer Ingenieur- und Architekten-VereinSIA (2009) Norm SIA 265/1: Holzbau – Ergänzende Festlegungen SIA, Zürich. 64 S
Skatter S, Kucera B (1998) The cause of the prevalent directions of the spiral grain patterns in conifers. Trees 12:265–273. https://doi.org/10.1007/s004680050150
Speidel G (1957) Die rechnerischen Grundlagen der Leistungskontrolle und ihre praktische Durchführung in der Forsteinrichtung: mit 57 Tabellen. Sauerländer Frankfurt/m 19:1–118
Steffenrem A, Kvaalen H, Høibø OA, Edvardsen ØM, Skrøppa T (2009) Genetic variation of wood quality traits and relationships with growth in *Picea abies*. Scand J for Res 24:15–27. https://doi.org/10.1080/02827580802641215
Tomppo E, Gschwantner T, Lawrence M, McRoberts RE (Eds.) (2010) National Forest Inventories: Pathways for Common Reporting. Springer Netherlands, Dordrecht, p 1–612. https://doi.org/10.1007/978-90-481-3233-1
UNE-EN 1927–2:2008 Qualitative classification of softwood round timber - Part 2: Pines. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0041458. Accessed 21 Jul 2022
UNE-EN 1316–1:2012a Hardwood round timber. Qualitative classification. Part 1: Oak and beech. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0009647. Accessed 21 Jul 2022
UNE-EN 1316–2:2012b Hardwood round timber - Qualitative classification - Part 2: Poplar. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0050494. Accessed 21 Jul 2022
Vauhkonen J, Berger A, Gschwantner T, Schadauer K, Lejeune P, Perin J, Pitchugin M, Adolt R, Zeman M, Johannsen VK, Kepfer-Rojas S, Sims A, Bastick C, Morneau F, Colin A, Bender S, Kovácsevics P, Solti G, Kolozs L, Nagy D, Nagy K, Twomey M, Redmond J, Gasparini P, Notarangelo M, Rizzo M, Makovskis K, Lazdins A, Lupikis A, Kulbokas G, Antón-Fernández C, Rego FC, Nunes L, Marin G, Calota C, Pantić D, Borota D, Roessiger J, Bosela M, Šebeň V, Skudnik M, Adame P, Alberdi I, Cañellas

I, Lind T, Trubins R, Thürig E, Stadelmann G, Ditchburn B, Ross D, Gilbert J, Halsall L, Lier M, Packalen T (2019) Harmonised projections of future forest resources in Europe. Ann for Sci 76:79. https://doi.org/10.1007/s13595-019-0863-6
Vidal C, Alberdi I, Redmond J, Vestman M, Lanz A, Schadauer K (2016) The role of European National Forest Inventories for international forestry reporting. Ann for Sci 73(4):793–806. https://doi.org/10.1007/s13595-016-0545-6
Vidal C, Alberdi I, Hernández L, Redmond JJ (2016a) National forest inventories: assessment of wood availability and use. Springer International Publishing Switzerland, p 1–845. https://doi.org/10.1007/978-3-319-44015-6
Wang X, Ross RJ, Carter P (2007) Acoustic evaluation of wood quality in standing trees. Part I. Acoustic wave behavior. Wood and Fiber Science 39 (1): 28–38. https://wfs.swst.org/index.php/wfs/article/view/299/299. Accessed 21 Jul 2022
Watt MS, Moore JR, Facon J, Downes J, Clinton PM, Coker G, Davis MR, Simcock R, Parfitt RL, Dando J, Mason EG, Bown HE (2006) Modelling the influence of stand structural, edaphic and climatic influences on juvenile Pinus radiate dynamic modulus of elasticity. For Ecol Manage 229:136–144. https://doi.org/10.1016/j.foreco.2006.03.016
Watt MS, Kimberley MO, Harrington JJ, Riddell MJ, Cown DJ, Moore JR (2013) Differences in intra-tree variation in spiral grain angle for radiata pine. NZ J Forest Sci 43:1–8. https://doi.org/10.1186/1179-5395-43-12
Wernsdörfer H, Constant T, Mothe F, Badia MA, Nepveu G, Seeling U (2005) Detailed analysis of the geometric relationship between external traits and the shape of red heartwood in beech trees (Fagus sylvatica L.). Trees 19:482–491. https://doi.org/10.1007/s00468-005-0410-y
Wessels CB, Malan FS, Rypstra T (2011) A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. Eur J Forest Res 130:881–893. https://doi.org/10.1007/s10342-011-0484-6

Publisher's Note