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Modelling resin production distributions for *Pinus pinaster* Ait. stands in NW Spain

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ABSTRACT

Pine resin, a viscous material secreted as a defensive response to biotic or abiotic damage, is a highly valuable non-wood forest product with multiple uses in the industrial sector. Resin production can be induced by tapping live trees, but not all pine species produce resin of suitable quality and/or in profitable quantities. Maritime pine (*Pinus pinaster* Ait.) is currently the only species tapped in Spain, where resin tapping activity has been recovered in the last few decades. Most studies on resin production focus on the mean production per tree or per area, and less attention is given to determining how the production is distributed across individuals or production classes. We modelled the distribution of resin production in *Pinus pinaster* stands in Galicia (NW Spain) by using the Weibull function and the moment-based parameter recovery method. We observed a high level of variance in resin production between plots (different sites, stimulants used, tapping method or year) and within plots, between trees. All resin production distributions modelled using the arithmetic mean resin production ($\overline{x}$) and the variance of the distribution (σ^2) per plot satisfied the Kolmogorov-Smirnov (KS) test, in which critical values were obtained by Monte Carlo simulation. The variance of the distribution (σ^2) was positively correlated with $\overline{x}$, and the relationship was described by an exponential model. When resin production distributions were modelled using $\overline{x}$ and estimated variance ($\hat{\sigma}^2$), 7% of the distributions (corresponding to trees in which chemical stimulants were not used) did not satisfy the KS test. The mean production ($\overline{x}$) can be easily determined by dividing the stand production by the number of trees. However, $\overline{x}$ could also be estimated before commercial tapping by sampling a representative number of trees. We conclude that in order to estimate $\overline{x}$, a minimum sample of 50–60 trees should be tapped, to yield a relative standard error (RSE) below 10%; 10–15 trees should be considered for RSE < 20% and 5–10 for RSE < 30%.

1. Introduction

Resin is a viscous material secreted by conifers, especially members of the genus *Pinus*, as a defensive response to biotic or abiotic damage (Rodríguez-García et al., 2016). It is composed of a volatile fraction (turpentine) and a non-volatile fraction (rosin). Resin has been used by humans since ancient times (Rodríguez García, 2016) and is currently considered a valuable non-wood forest product with multiple uses in the industrial sector (Rodrigues-Corrêa et al., 2013; Neis et al., 2019). Although similar products can be obtained from pine stumps or from black liquor soap during the kraft pulping process, resin production is usually induced by tapping live pine trees through wounds made on the stem (Coppen and Hone, 1995).

Resin tapping is not always profitable, and the quantity and quality of resin obtained is primarily determined by the species of pine considered (Coppen and Hone, 1995; Rodrigues-Corrêa et al., 2013). Maritime pine (*Pinus pinaster* Ait.), which is currently the only species tapped in western Mediterranean countries (Rodríguez-García et al., 2016), produces useful quantities of good quality resin (Coppen and Hone, 1995). Maritime pine is widely distributed in the western Mediterranean Basin and along the Atlantic coast of Portugal, Spain and France, in areas located at different elevations and characterised by different climatic conditions and edaphic properties (Alía and Martín, 2003; Fig. 1). It is the most widespread conifer in Spain, where resin tapping is concentrated in the Meseta Central, on sandy soils (Soliño et al., 2018). Resin tapping was an important economic activity in Spain until the 1970s, when it became unprofitable (Hernández Muñoz, 2006). However, resin production in Spanish forests has recovered in the last

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two decades and is now considered economically viable (Soliño et al., 2018). The "American" tapping method is used in Spain, Brazil, Argentina and Portugal (Rodrigues-Corrêa et al., 2013). The method was developed in the first half of 20th century by the USDA Forest Service for application in southern pines such as the longleaf pine (*Pinus palustris* Mill.) and slash pine (*Pinus elliottii* Engelm.) (Harrington, 1969; Clements, 1974). This method consists of removing strips of bark and phloem every 14 days and adding a sulphuric acid-based stimulant. However, other stimulant treatments have been tested over the years in several species (Rodrigues-Corrêa et al., 2013) and more recently in *P. pinaster* (Michavila et al., 2020). In Spain, tapping is seasonal, starting between March and June and ending in October-November, when climatic conditions are favourable (Rodríguez-García et al., 2015).

Resin tapping is not a traditional activity in Galicia (NW Spain), unlike in the Meseta Central. However, the boom in resin production in Spain between the early 1950s and the early 1970s led to research into the potential for production in different regions. As a result of the current recovery of resin production in Spain, the interest in resin production has also been reactivated in Galicia, where pure stands of maritime pine cover an area of 217,281 ha (MMAMRM, 2011). Resin tapping could be a valuable economic activity in the region, and it also has environmental and social benefits, such as contributing to reducing forest fires and generating rural employment (Soliño et al., 2018). In contrast to resin production in the Meseta Central, production in Galicia must be secondary to and compatible with the production of quality timber (Martínez Chamorro, 2016). In the 1930s, the compatibility between timber and resin production was also promoted in southern pine forests in the U.S.A. (Harrington, 1969), where resin tapping a few years prior to timber harvesting was recommended. In the long term, resin tapping reduces tree growth and generates scars inside the stem that are not compatible with quality timber production. For example, Génova et al. (2014) reported a reduction in diameter growth of 33% for long-term resin tapping in *P. pinaster* in central Spain. Likewise, Harrington (1969) reported a reduction of about 25% in volume growth per year in *P. elliottii* when tapping one face, as also reported by Clements (1974), and a reduction of about 50% when two faces were tapped. Therefore, in Galicia, resin production is being considered for pine stands due to be harvested in the near future (2–5 years), with a rotation age at 30–50 years depending on quality site and timber destination. Ongoing regional studies of resin tapping consider site quality, and methodological aspects of different tapping methods (e.g. the number of faces, the wound size or the chemical stimulant).

Most studies on resin production focus on mean production per tree or per area, but less attention is given to the distribution of production. Modelling the distribution of resin production highlights the contribution of each class to the total production and could be useful for resin tree breeding programmes (Prada et al., 1997), for developing resin production models or combined resin and timber production models (Nanos et al., 2000), as well as for evaluating resin productivity, considering that there is no difference in the time and cost involved in tapping high-producing and low-producing trees. The Weibull function has been widely used in modelling forest distributions because of its flexibility and simplicity. This function was first used to model diameter distributions by Bailey and Dell (1973) and later also applied in modelling other forest distributions, including resin production (Nanos et al., 2000). Several methods have been developed to predict the Weibull function parameters, but there is no clear reason for choosing one approach over another (Cao, 2004). Selecting the parameter recovery method has the advantage that the attributes from the observed (empirical) distribution used in the recovery process will be the same as those in the predicted distribution (Siipilehto and Mehtätalo, 2013).

The overall objective of the present study was to model the distribution of resin production in *Pinus pinaster* stands in NW Spain by using the Weibull function. The specific objectives were as follows: (i) to recover the parameters of the Weibull function in each plot from the observed mean production and variance, corresponding to real-scale tapping activity; (ii) to study the possibility of modelling distributions with the observed mean production and estimated variance; and (iii) to test the goodness-of-fit of predicted distributions in both cases, with and without observed variance.

2. Material and methods

2.1. Study area and data

The study was carried out in the temperate climate region of Galicia (NW Spain). Three even-aged maritime pine (*P. pinaster*) stands were selected for study: Caldas de Reis, Maceda and Porto do Son, in the provinces of Pontevedra, Ourense and A Coruña, respectively (Fig. 1). All three stands were naturally regenerated, and thinnings had been

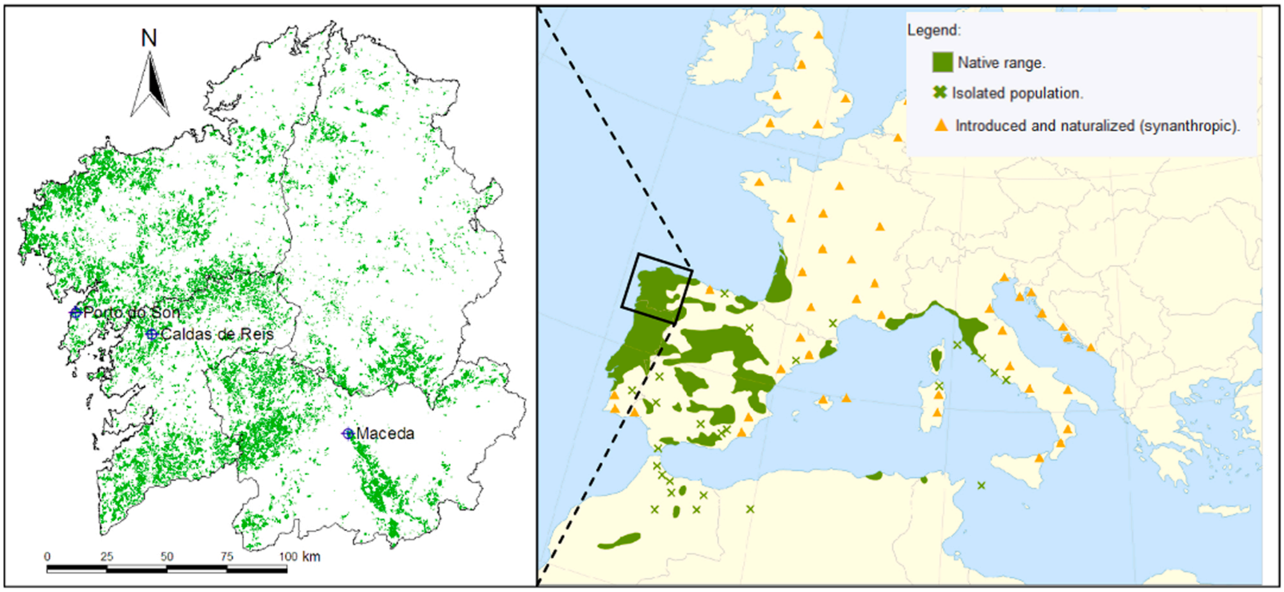


Fig. 1. Right: map showing the distribution of *Pinus pinaster* (Maritime pine) according to EUFORGEN (www.euforgen.org). Left: Location of experimental sites in Galicia with the Maritime pine stands overlaid.
(source: Spanish Forest Map).

carried out to reduce tree density. Unhealthy or small trees (diameter at breast height less than 20 cm) were excluded from the study. The selected trees were individually labelled, and dendrometric measurements were made before tapping (Table 1). Research experiments with the same design were established in 2016 in Caldas de Reis and in 2017 in Maceda. The experimental design consisted of three completely randomized blocks, with an elementary plot of 50 trees, 6 treatments and 3 years of production. As the present study focuses on the wound tapping method, we considered 4 treatments: the traditional one-face method with a 12 cm wound, one-face with 16 cm wound, and simultaneous tapping of two faces (with 12 and 16 cm wound). As new questions emerged, we conducted additional experiments with fewer trees than in the previous experiments to determine the following: (a) the effects of chemical stimulants in Maceda (in 2017, 2018 and 2019), and (b) in the one-face method, the response to a large wound size (20 cm) relative to the traditional (12 cm) wound, both in Caldas de Reis (2019 and 2020) and in Porto do Son (2020). In Maceda, we tested three stimulant pastes, all of which contained sulphuric acid: a) "salicylic paste" (25% sulphuric acid 96% v/v, 1% salicylic acid, 50% distilled water, 5% propylene glycol, 19% wheat straw), b) "ethephon paste" (Michavila et al., 2020) (14% sulphuric acid 50% v/v, 8% ethephon 60% v/v, 55% distilled water, 1.7% polysorbate, 1% cetyl alcohol, 4% vaseline, 5.5% silica, 10.8% sawdust), and c) "white paste", a stimulant traditionally used in Spain (79% sulphuric acid 45% v/v, 21% plaster). We also included tapped trees not treated with stimulant as control trees. Trees not included in the stimulant experiment were all stimulated with the ethephon-based paste.

The objective of the present study was to model the production distribution in resin plots, where the plot is defined as the combination of site, stimulant, tapping method (number of faces and wound size) and year (Table 2). Moreover, when studying the one-face method with 12 cm and 20 cm wounds, we also considered whether trees had been tapped previously. We thus used 45 plots with a minimum of 42 trees and a maximum of 150 trees, which yielded a total of 5058 observations. Overall, the tapping method consisted of removing horizontal strips of bark and phloem with a manual tool every 14 days, working upwards in the tree, beginning in March-June and finishing in October-November. In most cases, a strip of stimulant paste was placed in the upper-inside border of each groove made at 14-day intervals. The resin flow was collected in a semi-rigid "pot shaped" container with a capacity of approximately 2 kg. For each tree, face and groove, the containers with resin were weighed with an electronic hanging scale (Kern HDB-5K5N) of maximum capacity 5 kg and accuracy of 5 g (Kern and Sohn GmbH, 2021). Resin production was calculated per groove, by subtracting the container weight. The variable modelled was annual production per tree (g tree^{-1}).

2.2. Recovery of Weibull parameters by the method of moments

We first checked that resin production distributions were unimodal, by constructing frequency histograms. Then, instead of the three-parameter function, we selected the two-parameter Weibull function (Eq. (1)), which facilitates estimation of the function parameters without the precision of estimations being seriously affected (Diéguez-Aranda et al., 2009).

$$f(x) = \left(\frac{c}{b}\right)\left(\frac{x}{b}\right)^{c-1}\exp\left[-\left(\frac{x}{b}\right)^{c}\right], \tag{1}$$

where x is the random variable, b is the scale parameter of the function, and c is the shape parameter that controls the skewness.

In the first step, the function parameters were recovered from the first raw moment, which was the arithmetic mean resin production ($\overline{x}$), and the second central moment, which was the variance of the distribution (σ^2), with Eqs. (2) and (3) (Cao et al., 1982).

$$\sigma^2 = \frac{\overline{x}^2}{\Gamma^2\left(1+\frac{1}{c}\right)}\left[\Gamma\left(1+\frac{2}{c}\right) - \Gamma^2\left(1+\frac{1}{c}\right)\right] \tag{2}$$

$$b = \frac{\overline{x}}{\Gamma\left(1+\frac{1}{c}\right)}, \tag{3}$$

where Γ is the Gamma function.

Once the mean and the variance of the resin production distribution are known, parameter c can be obtained using an iterative procedure, as Eq. (2) only depends on this parameter. Parameter b can then be calculated directly from Eq. (3).

In a second step, plot-variance (σ^2) was plotted against other plot variables to test the possibility of estimating σ^2, in order to facilitate modelling of the resin production distributions. As a relationship between plot-variance and plot-mean production was detected, the PROC MODEL procedure of SAS® software (SAS Institute Inc., 2014) was used for model fitting. We tested well-known two- and three-parameters models. Heteroscedasticity is sometimes detected during modelling and causes two main problems (Myers, 1990): the parameter estimates are no longer efficient, and the statistical tests are not valid. Although heteroscedasticity cannot be corrected, it can be taken into account in model fitting using the generalized method of moments (GMM) (Greene, 1999).

2.3. Goodness-of-fit

We used the Kolmogorov-Smirnov (KS) test to assess the suitability of the two-parameter Weibull function and parameter recovery method used to describe the resin production distributions. The KS test compares an empirical distribution $F_n(x)$ with a theoretical completely specified continuous distribution $F_0(x)$ by calculating the D statistic (Cao, 2004; Eq. (4)).

$$D = \sup_x |F_n(x) - F_0(x)| = \max\left\{\begin{array}{c} \max_{1\le i\le n_i} F_n(x_i) - F_0(x_j), \\ \max_{1\le i\le n_i} F_0(x_j) - F_n(x_{i-1}) \end{array}\right\}, \tag{4}$$

where sup$_x$ is the supreme of the set of distances.

D is compared with tabulated or calculated critical D values at a specified significance level (α). However, when the parameters of the theoretical distribution are not known and must be estimated from the

Table 1

Description of the experimental sites.

Site	Geographical coordinates	Elevation (m)	Area (ha)	Year	Stand age	d_m	h_m	N
Caldas de Reis	42° 37′ N 8° 36′ W	250	2.90	2016	27	33.2 (6.4)	19.0 (1.5)	327
Maceda	42° 14′ N 7° 37′ W	540	5.86	2017	56	41.8 (7.9)	24.8 (2.2)	222
Porto do Son	42° 42′ N 8° 59′ W	275	1.42	2020	28	32.0 (5.9)	12.9 (1.4)	265

Elevation: m above sea level; year reflects the start of the experiments and dasometric measurements, and stand age corresponds to that year; d_m: mean diameter at breast height (cm); h_m: mean total tree height (m); standard deviations for dm and hm are shown in brackets; N: number of trees per hectare.

Table 2

Plots used to model resin production distributions. Plot is defined as the combination of site, stimulant, tapping method (number of faces and wound size), year and whether trees were previously tapped or not. The plot number is shown in bold and the number of trees (observations) per plot, in brackets.

Site	Stimulant	Number of faces	Wound size (cm)	Year				
				2016	2017	2018	2019	2020
1	B	1	12[1]	**1** (150)	**2** (148)	**3** (147)	**34** (45) **36** (42)	**35** (45) **37** (42)
1	B	1	16	**4** (150)	**5** (148)	**6** (148)		
1	B	2	12	**7** (150)	**8** (149)	**9** (149)		
1	B	2	16	**10** (150)	**11** (150)	**12** (149)		
1	B	1	12				**38** (44)	**39** (44)
1	B	1	20				**40** (44)	**41** (43)
2	A	1	12		**13** (120)	**14** (120)	**15** (120)	
2	B	1	12		**16** (150)	**17** (149)	**18** (149)	
2	C	1	12		**19** (120)	**20** (120)	**21** (120)	
2	D	1	12		**22** (60)	**23** (60)	**24** (60)	
2	B	1	16		**25** (150)	**26** (148)	**27** (146)	
2	B	2	12		**28** (150)	**29** (148)	**30** (147)	
2	B	2	16		**31** (150)	**32** (147)	**33** (147)	
3	B	1	12					**42** (60)
3	B	1	12[a]					**43** (60)
3	B	1	20					**44** (60)
3	B	1	20[a]					**45** (60)

Site: (1) Caldas de Reis, (2) Maceda and (3) Porto do Son; Stimulants: (A) “salicylic paste”, (B) “ethephon paste”, (C) “white paste”, the stimulant traditionally used in Spain, and (D) no stimulant; [1] the initial one-face with a 12 cm wound was partly divided, in 2019 and 2020, into one-face 12 cm wound (plots 34 and 35) and 20 cm wound (plots 36 and 37).

[a] previously tapped in two years with one-face and a 12 cm wound.

empirical distribution, tabulated critical D values are no longer valid (Lilliefors, 1967). In this case, the critical D values should be obtained by Monte Carlo simulation. Therefore, for each plot we generated 10,000 independent, identically distributed pseudo-random samples. We used the *rand* function in SAS® software (SAS Institute Inc., 2014) to generate pseudo-random Weibull samples with a size equal to the number of observations per plot and from recovered parameters. We calculated D for each simulation, and calculated the D distribution with the 10,000 simulations per plot ($D_{\mathrm{MonteCarlo}}$ distribution). For each plot, the critical D value (D_{crit}) for an α level was taken from the 1- α quantile of $D_{\mathrm{MonteCarlo}}$ distribution. We applied a significance level of 5%.

As mean-plot production ($\bar{x}$) is a key value in this study, the accuracy of estimating $\bar{x}$ per plot was evaluated by the relative standard error (RSE, Eq. (5)).

$$\mathrm{RSE}\ (\%) = 100\,\frac{Z\frac{\sigma}{\sqrt{n}}}{\bar{x}}, \tag{5}$$

where Z is a standard Z-score for the desired level of confidence ($Z = 1.96$ for a 95% confidence interval), σ is the standard deviation, n is the number of observations, and $\bar{x}$ is the mean.

In plot-variance estimation, comparison of the estimates of the different models tested was based on numerical and graphical analyses, which involved plotting residuals against the estimated values. The numerical analysis consisted of comparing two statistical criteria obtained from the residuals (Myers, 1990): the coefficient of determination (R^2, Eq. (6)), which measures the amount of observed variability explained by the model, and the root mean squared error (RMSE, Eq. (7)), which provides a measure of the precision of the estimates in the same units as the dependent variable.

$$R^2 = 1 - \frac{\sum_{i=1}^{i=n}\left(Y_i - \widehat{Y}_i\right)^2}{\sum_{i=1}^{i=n}\left(Y_i - \overline{Y}\right)^2} \tag{6}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{i=n}\left(Y_i - \widehat{Y}_i\right)^2}{n-p}}, \tag{7}$$

where Y_i, $\widehat{Y}_i$, and $\overline{Y}$ are respectively the measured, estimated and average values of the dependent variable, n is the total number of observations used to fit the model, and p is the number of model parameters.

3. Results and discussion

A high level of inter- and intra-plot variance in resin production was observed (Table 3, Fig. 2). Among plots, the mean-plot production varied from 335 to 5090 g tree^{-1}. The minimum mean production per plot corresponded to the experiments involving chemical stimulants, specifically from control trees in which no stimulant was applied (1–12-D in Fig. 2, corresponding to plots 22, 23 and 24), with mean production in the range 335–392 g resin tree^{-1}. The mean production in these three plots ranged between 11% and 13% of the global mean production (3048 g tree^{-1}). When the data from plots 22, 23 and 24 were excluded from the analysis, the mean-plot production ranged from 1594 to 5090 g tree^{-1}. In the study plots in Galicia, the traditional resin-tapping method (one-face with a 12 cm wound) generated a mean production ranging from 1594 to 4001 g tree^{-1}, with an average of 2646 g tree^{-1}, which is lower than resin production in other Spanish regions (3.2–3.5 kg tree^{-1}) cited by Pinillos et al. (2009) and close to the minimum range (2.5–3.5 kg tree^{-1}) cited by Montero González (2018). However, the optional methods of two-face tapping or opening wider wounds provide ways of improving tapping production in Galicia (e.g. in the one-face method with a 20 cm wound, the mean-plot production range was 3558–4802 g tree^{-1}). Coppen and Hone (1995) pointed out that the minimum acceptable yearly resin production is around 2 kg tree^{-1} and that production is considered suitable at 3–4 kg tree^{-1}. However, productivity is also important, and lower production can be profitable if less labour is required.

When we modelled production in case I (parameter recovery method using observed mean production and variance), all modelled Weibull distributions satisfied the Kolmogorov-Smirnov (KS) test at a significance level of 5% (Table 3). In 37 of the 45 plots, the Weibull function was positively skewed, because parameter c ranged between 1 and 3.6 (Diéguez-Aranda et al., 2009). Therefore, in most distributions (82%), the mean was higher than the mode and the median, as also observed by Nanos et al. (2000).

The observed positive relationship between plot-variance and mean plot production (Fig. 3a) was also observed by Nanos et al. (2000). After numerical and graphical analyses, the exponential model (Eq. 8) was

Table 3
Descriptive statistics for resin production per plot; including number of trees (observations, n), mean production (g tree^{-1}), maximum (Max), minimum (Min) and variance (σ^2). Estimation of two-parameters Weibull function (*c* and *b*) using the parameter recovery method through moments with (I) variance observed (σ^2) and (II) variance estimated with Eq. (8) ($\widehat{\sigma}^2$). In both cases (I and II), the Kolmogorov-Smirnov (KS) test was used to assess goodness-of-fit by calculation of the *D* statistic with Eq. (4) and the critical *D* value (*D*crit) by Monte Carlo simulation.

Plot	n	Mean	Max	Min	I					II				
					σ^2	*c*	*b*	*D*	*D*crit	$\widehat{\sigma}^2$	*c*	*b*	*D*	*D*crit
1	150	2163	4215	945	400733	3.82	2392	0.084	0.111	609745	3.02	2421	0.099	0.110
2	148	3421	6985	475	1129745	3.57	3798	0.051	0.110	1400684	3.17	3821	0.071	0.111
3	147	2690	5562	427	908282	3.09	3009	0.052	0.111	863990	3.17	3005	0.051	0.111
4	150	2377	7270	230	608868	3.36	2648	0.077	0.110	702549	3.10	2658	0.096	0.109
5	148	3410	9202	1420	1374449	3.19	3808	0.080	0.110	1390779	3.17	3809	0.080	0.110
6	148	2665	6257	502	959506	2.96	2986	0.087	0.110	849552	3.17	2976	0.088	0.109
7	150	3048	6080	1205	1002664	3.36	3395	0.061	0.110	1094929	3.20	3404	0.062	0.109
8	149	4470	9962	1265	2883296	2.86	5016	0.054	0.109	2801522	2.90	5013	0.057	0.110
9	149	3404	7444	729	1961148	2.61	3832	0.056	0.110	1385333	3.17	3803	0.098	0.110
10	150	3513	6930	1190	1494682	3.15	3925	0.061	0.110	1488498	3.16	3925	0.061	0.109
11	150	5090	11714	1555	4470866	2.58	5732	0.060	0.109	4222284	2.67	5726	0.059	0.109
12	149	3799	8979	949	2780017	2.43	4285	0.065	0.110	1798609	3.10	4248	0.072	0.109
13	120	2042	5294	452	681234	2.66	2297	0.065	0.123	562889	2.96	2288	0.065	0.123
14	120	1674	3780	470	476193	2.61	1885	0.047	0.122	441387	2.72	1882	0.057	0.122
15	120	2015	4327	262	679281	2.63	2267	0.058	0.122	552859	2.95	2258	0.072	0.122
16	150	2771	6896	1037	922616	3.16	3096	0.052	0.108	911657	3.18	3095	0.051	0.109
17	149	2169	5885	425	758274	2.68	2440	0.058	0.110	612314	3.03	2428	0.056	0.110
18	149	2380	6147	407	965525	2.60	2680	0.046	0.109	703969	3.10	2661	0.080	0.111
19	120	1673	4237	577	611572	2.26	1888	0.071	0.123	440974	2.72	1880	0.113	0.124
20	120	1594	3995	570	459853	2.52	1797	0.084	0.122	418768	2.65	1794	0.089	0.123
21	120	1905	3952	427	701661	2.43	2149	0.070	0.123	514342	2.89	2137	0.111	0.123
22	60	392	1117	147	28953	2.46	441	0.079	0.174	189084	0.90	372	0.377	0.173
23	60	383	835	125	22982	2.73	430	0.113	0.172	187993	0.88	360	0.392	0.174
24	60	335	637	147	14827	3.00	375	0.090	0.174	182102	0.79	293	0.450	0.173
25	150	2759	5247	82	904422	3.18	3082	0.044	0.109	904470	3.18	3082	0.044	0.111
26	148	2198	4937	45	653574	2.96	2462	0.050	0.111	623890	3.04	2460	0.047	0.111
27	146	2668	5634	562	1103540	2.74	2998	0.058	0.111	851305	3.17	2980	0.068	0.111
28	150	4363	7509	1229	1476165	4.03	4811	0.078	0.110	2610583	2.94	4890	0.096	0.110
29	148	3402	7020	1120	1211402	3.41	3786	0.076	0.110	1382820	3.17	3800	0.066	0.109
30	147	3621	7929	589	1711595	3.02	4054	0.078	0.111	1598666	3.14	4047	0.073	0.110
31	150	4813	10129	1994	2382028	3.45	5354	0.059	0.111	3515641	2.78	5407	0.084	0.109
32	147	3814	8080	1345	1821365	3.09	4265	0.070	0.111	1815548	3.10	4264	0.071	0.112
33	147	4177	8789	1729	2332595	2.98	4679	0.068	0.112	2308173	3.00	4677	0.069	0.110
34	45	3666	6617	1917	1070842	3.97	4046	0.078	0.200	1646874	3.13	4098	0.123	0.198
35	45	4001	7085	2215	1403955	3.77	4429	0.117	0.201	2054927	3.05	4477	0.117	0.200
36	42	4500	8602	1372	2738027	2.96	5042	0.095	0.204	2858582	2.89	5048	0.096	0.206
37	42	4802	10650	40	5608093	2.13	5423	0.093	0.204	3490435	2.78	5395	0.102	0.205
38	44	3025	5772	1527	866250	3.61	3356	0.100	0.202	1078043	3.20	3377	0.097	0.198
39	44	3606	5395	1935	1105064	3.83	3988	0.070	0.202	1582742	3.14	4030	0.082	0.200
40	44	3665	6067	1652	1375238	3.46	4076	0.065	0.198	1646230	3.13	4097	0.068	0.201
41	43	4381	7990	1295	2588873	2.97	4908	0.060	0.201	2641563	2.93	4911	0.062	0.201
42	60	3103	7837	1252	2096092	2.27	3503	0.112	0.172	1135367	3.20	3465	0.143	0.172
43	60	3725	7897	1337	1991758	2.86	4180	0.110	0.171	1712463	3.12	4164	0.101	0.172
44	60	3558	5922	2112	876717	4.29	3910	0.136	0.171	1533608	3.15	3976	0.130	0.174
45	60	3918	6692	1602	1572135	3.46	4357	0.110	0.173	1945046	3.07	4383	0.115	0.173

Note: For information about plots, see Table 2.

selected to predict plot-variance ($\widehat{\sigma}^2$) from arithmetic mean resin production per plot ($\overline{x}$, g tree^{-1}). The plot of residuals against predicted values (Fig. 3b) revealed a random pattern around zero with no detectable significant trends, but heteroscedastic residuals. We therefore used the GMM method for model fitting. The fitted model explained 78% of the observed variability, and both parameters were significant at the 5% level (Table 4).

$$\widehat{\sigma}^2 = a \exp(b\,\overline{x}) \tag{8}$$

When modelling Weibull distributions with variance estimated with Eq. (8) (Case II), 3 of the 45 distributions did not satisfy the Kolmogorov-Smirnov (KS) test at the 5% significance level (Table 3). The three distributions which did not satisfy the KS test corresponded to the already cited plots 22, 23 and 24.

Graphical representation of observed and estimated cumulative relative frequencies against resin production (Fig. 4) showed that the estimation was improved by using observed plot-variance; however, in most cases, only slight differences were obtained by using estimated plot-variance. The mean-plot production ($\overline{x}$) can easily be determined at the end of the tapping season by dividing the total production by the number of trees. Prior estimation of mean production would further increase the capacity of support decision-making, which is especially important in regions such as Galicia where resin tapping is not traditionally carried out (Zas et al., 2020a). However, no models that predict accurately resin production before tapping have yet been developed, because production depends on several correlated variables. In *P. pinaster*, resin production is related to (i) tree variables such as size, age and wood anatomy (Rodríguez-García et al., 2014; Zas et al., 2020a), (ii) climate variables (Rodríguez-García et al., 2015; Zas et al., 2020b) and (iii) the tapping method, including the wound size, number of faces, length of season and stimulant used (Michavila et al., 2020). Many of these variables were already identified by the USDA Forest Service during development of the American tapping method (Harrington, 1969; Clements, 1974). Variables related to tree size or vigour are known to involve resin production (Schopmeyer and Larson, 1955; Ruel et al., 1998; Lombardero et al., 2000; Rodrigues et al., 2008) and

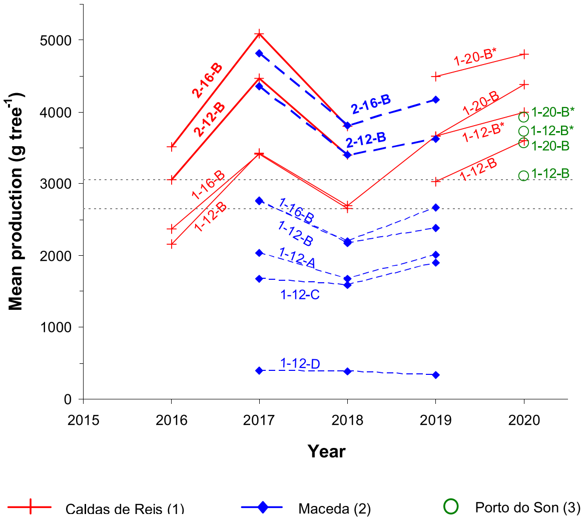
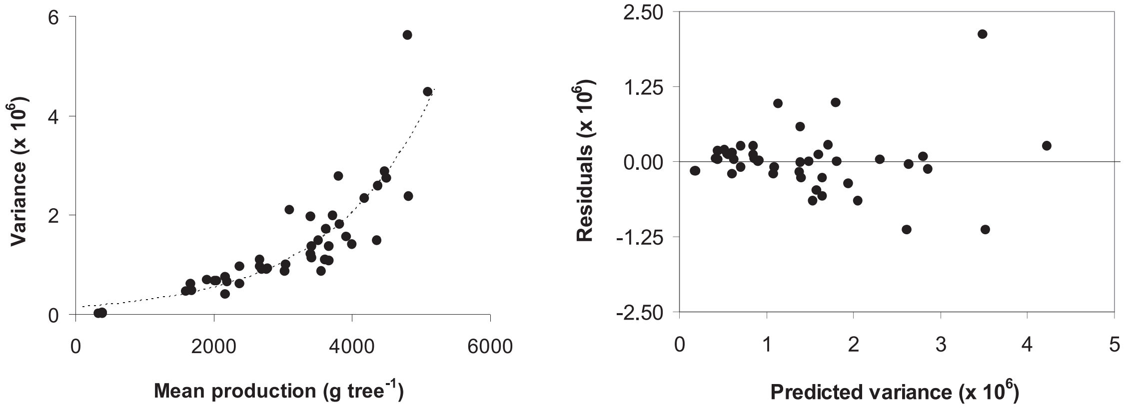


Fig. 2. Mean production ($\bar{x}$, g tree^{-1}) in each site, stimulant used and tapping method used in the different years. Each dot (cross, rhombus or circle) represents a mean-plot production in this study. Sites are represented in different colours, and different symbols (cross, rhombus or circle). The three character codes (e.g. 2–16-B) indicate the number of faces per tree, wound of each face (cm) and stimulant used, respectively. The two-face method is highlighted in bold. The stimulant pastes are given in Table 2 and a detailed description in *Material and Methods*. The upper horizontal line represents the global mean production in this study (3048 g tree^{-1}) and the lower horizontal line represent the mean production in the traditional Spanish resin-tapping method (one-face with a 12 cm wound, 2646 g tree^{-1}).

also climate variables, including intra- and inter-annual effects (Lombardero et al., 2000; Rodrigues and Fett-Neto, 2009; Neis et al., 2018). In the present study, the favourable climatic conditions during 2017 and the unfavourable conditions in 2018 resulted in highs and lows in resin production (Fig. 2), highlighting the difficulty in accurately predicting mean production. From the three groups of variables described above, related to resin production, the group of climatic variables is, of course, outside of our control.

Although resin production cannot be accurately predicted before tapping, one possible way of predicting resin production potential would be to use an empirical test in a representative number of trees. In this study, the relative standard error (RSE, Eq. (5)) associated with calculation of mean resin production per plot ($\bar{x}$, g tree^{-1}) ranged from 7.4% to 14.9% (confidence level, 95%). Our data suggest that a minimum of 50–60 trees should be sampled to maintain the RSE associated with calculation of $\bar{x}$ below 10%, 10–15 trees for RSE $<$ 20% and 5–10 trees for RSE $<$ 30%. Greater accuracy is required in research experiments involving improvements in tapping methods or stimulants; however, in practice, resin production potential could be estimated for around 10 trees. Evaluation of production from sampled trees should also take into account whether the climatic conditions during the sampling year were favourable or not. A less expensive alternative for evaluating resin potential could be tapping trees by removing small portions of bark and phloem (“microtapping”) and use plastic vial samplers to collect the resin over the subsequent few days (Karsky et al., 2004). This method has been shown to be valid for accurate evaluation of resin potential at stand level (but not at tree level) in Atlantic maritime pine forest (Zas et al., 2020a). Potential production could even be tested in young pine trees (De Oliveira Junkes et al., 2019).

Complementary production of resin, bioenergy (Gómez-García, 2021) and mushrooms (Calama et al., 2010) could contribute to pine stands becoming more profitable in Galicia where the area covered by pine has decreased in the last decades. In order to consider other possible scenarios in forest regional policies, further investigation in resin production is necessary. In the long term, genetic improvement could be directed towards the combined production of timber and resin (Alía and Martín, 2003; Zas et al., 2020a, 2020b). In the short-term, tapping could also be improved at the regional scale by e.g. the introduction of mechanization, the development of new stimulants, increasing the interval between grooves and by reducing the length of the tapping season. We are currently testing improvements in the region in accordance with the circular bioeconomy and with the aims of



(a)

(b)

Fig. 3. (a) Relationship between variance and mean production. The filled dots represent the fitted model (Eq. (8)); (b) residuals against the estimated values for Eq. (8).

Table 4
Parameter estimates, approximate significance and goodness-of-fit statistics for Eq. (8) fitted with the GMM method.

Model	Parameter	Estimate	Approx. std. error	t-value	Approx. p-value	RMSE (g tree^{-1})^2	R^2
$\hat{\sigma}^2 = a\exp(b\,\bar{x})$	a	145971	30480	4.79	$<$ 0.001	520197	0.777
	b	0.0006610	0.000061	10.81	$<$ 0.001		

$\hat{\sigma}^2$= estimated plot-variance (g tree^{-1})^2; $\bar{x}$= arithmetic mean resin production per plot (g tree^{-1}).

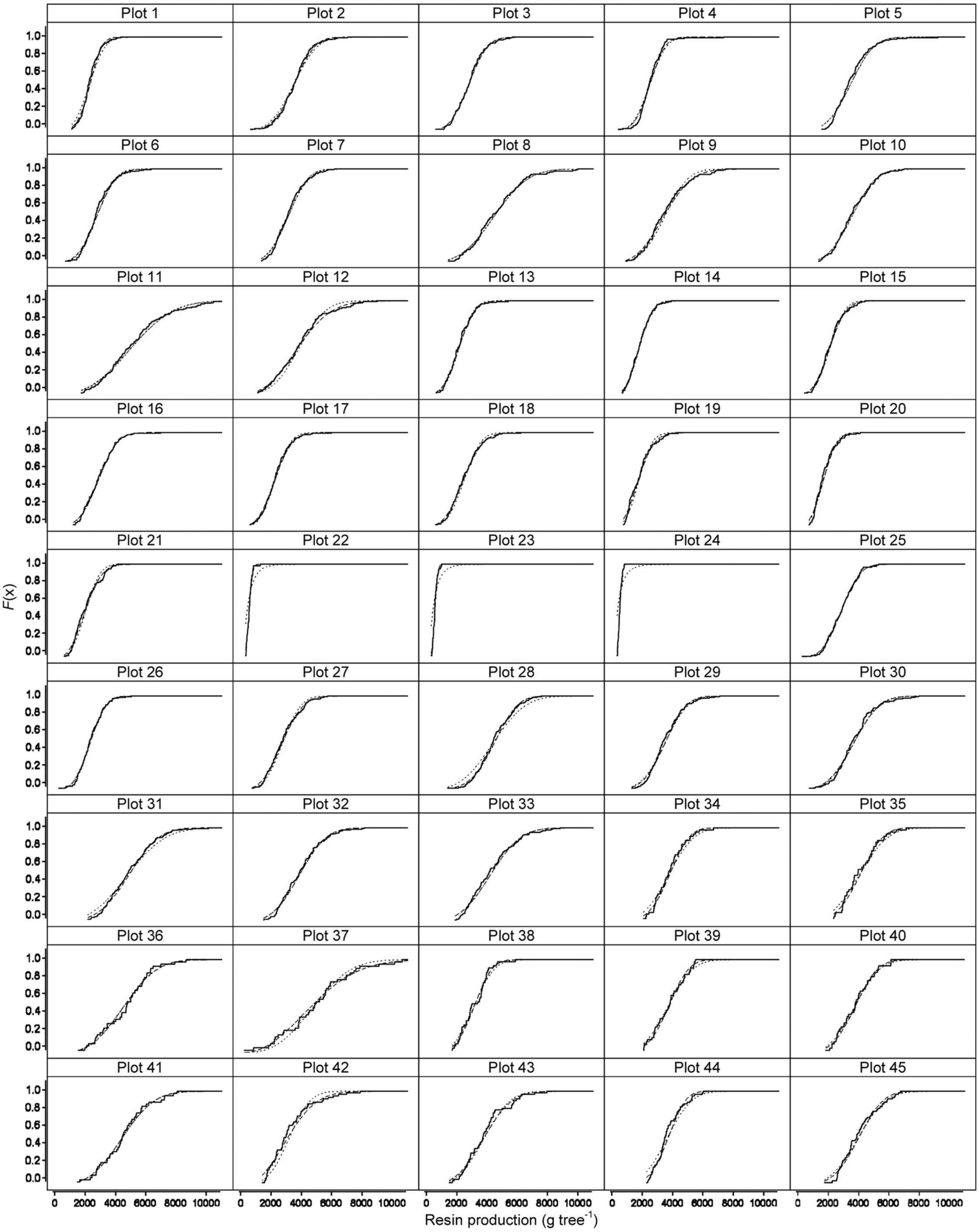


Fig. 4. Cumulative relative frequencies against resin production (g tree^{-1}) per plot. Continuous lines represent the empirical distributions (observed production); dashed lines represent the distribution functions estimated with the observed mean and variance; and the filled dots represent distribution function estimated with the observed mean and the estimated variance.

reducing labour costs as well as improving the working conditions for forest workers.

4. Conclusions

Resin production by tapping *Pinus pinaster* Ait. stands in NW Spain varies widely between plots (different sites, stimulant used, tapping method or year) and within plots, between trees. Resin production distributions per plot can be modelled using the two-parameter Weibull function and the moments-based parameter recovery method. The method uses the arithmetic mean resin production ($\overline{x}$) and the variance of the distribution (σ^2) per plot. With the observed $\overline{x}$ and σ^2 values, all modelled distributions satisfied the Kolmogorov-Smirnov (KS) test, for which critical values were obtained by Monte Carlo simulation. Plot variance (σ^2) can be estimated from the mean ($\overline{x}$) by using an exponential model. With estimated variance ($\widehat{\sigma}^2$), 7% of distributions (equal to control plots in a study of stimulants) did not satisfy the Kolmogorov-Smirnov (KS) test. For practical purposes, estimation of σ^2 makes modelling resin production distributions easier because the value of $\overline{x}$ can be determined by dividing the stand production by the number of trees.

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CRediT authorship contribution statement

E. Gómez-García: Investigation, Conceptualization, Methodology, Formal analysis, Writing. **E. Martínez Chamorro:** Investigation, Funding acquisition. **A. García-Méijome:** Investigation, Data curation. **M.J. Rozados Lorenzo:** Investigation, Review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alía, R., Martín, S., 2003. EUFORGEN Technical Guidelines for Genetic Conservation and use for Maritime pine (*Pinus pinaster*). International Plant Genetic Resources Institute, Rome, Italy.

Bailey, R.L., Dell, T.R., 1973. Quantifying diameter distributions with the Weibull function. For. Sci. 19, 97–104.

Calama, R., Tomé, M., Sánchez-González, M., Miina, J., Spanos, K., Palahí, M., 2010. Modelling non-wood forest products in Europe: a review. For. Syst. 19, 69–85.

Cao, Q.V., 2004. Predicting parameters of a Weibull function for modelling diameter distributions. For. Sci. 50, 682–685.

Cao, Q.V., Burkhart, H.E., Lemin, R.C., 1982. Diameter distributions and yields of thinned loblolly pine plantations. School of Forestry and Wildlife Resources, VPI and SU, Publication No. FSW-1–82.

Clements, R.W., 1974. Modern gum naval stores methods. USDA Forest Service, Asheville, North Carolina, Gen. Tech. Rep. SE-7.

Coppen, J.J.W., Hone, G.A., 1995. Gum Naval Stores: Turpentine and Rosin from Pine Resin. Natural Resources Institute. FAO, Rome.

De Oliveira Junkes, C.F., Vigne Duz, J.V., Kerber, M.R., Wieczorek, J., Galvan, J.L., Fett, J.P., Fett-Neto, A.G., 2019. Resinosis of young slash pine (*Pinus elliottii* Engelm.) as a tool for resin stimulant paste development and high yield individual selection. Ind. Crops Prod. 135, 179–187.

Diéguez-Aranda, U., Rojo Alboreca, A., Castedo-Dorado, F., Álvarez-González, J.G., Barrio-Anta, M., Crecente-Campo, F., González González, J.M., Pérez-Cruzado, C., Rodríguez Soalleiro, R., López-Sánchez, C.A., Balboa-Murias, M.A., Gorgoso Varela, J.J., Sánchez Rodríguez, F., 2009. Herramientas selvícolas para la gestión forestal sostenible en Galicia. Xunta de Galicia (in Spanish).

Génova, M., Caminero, L., Dochao, J., 2014. Resin tapping in *Pinus pinaster*: effects on growth and response function to climate. Eur. J. For. Res. 133, 323–333.

Gómez-García, E., 2021. Estimation of primary forest harvest residues and potential bioenergy production from fast-growing tree species in NW Spain. Biomass Bioenergy 148, 106055.

Greene, W.H., 1999. Econometric Analysis, 4th ed. Prentice Hall, Upper Saddle River, NJ.

Harrington, T.A., 1969. Production of oleoresin from southern pine trees. For. Prod. J. 19 (6), 31–36.

Hernández Muñoz, L., 2006. El antiguo oficio de resinero. Hojas divulgativas nº 2116 HD. Ministerio de Agricultura, Pesca y Alimentación. Gobierno de España.

Karsky, D., Strom, B., Thistle, H., 2004. An improved method for collecting and monitoring pine oleoresin. 0434-2306-MTDC. Missoula, MT. USDA Forest Service, Missoula Technology and Development Center.

Kern and Sohn GmbH, 2021. Hanging scale HDB-N/HDB-XL. Available at: ⟨https://www.kern-sohn.com/shop/en/industrial-scales/hanging-scales-crane-scales/HDB-N/HDB-XL/⟩ (Accesed 15 February 2021).

Lilliefors, H.W., 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. J. Am. Stat. Assoc. 62 (318), 399–402.

Lombardero, M.J., Ayres, M.P., Lorio, P.L., Ruel, J.J., 2000. Environmental effects on constitutive and inducible resin defences of *Pinus taeda*. Ecol. Lett. 3 (4), 329–339.

Martínez Chamorro, E., 2016. Revisión de las primeras experiencias de resinación en Galicia (1950-1970). Rev. IBADER Recur. Rurais 12, 13–22.

Michavila, S., Rodríguez-García, A., Rubio, F., Gil, L., López, R., 2020. Salicylic and citric acid as promising new stimulants for resin tapping in maritime pine (*Pinus pinaster* Ait.). For. Syst. 29 (3), eSC07.

MMAMRM (Spanish Ministry of Environment, Rural and Marine), 2011. Cuarto Inventario Forestal Nacional, Comunidad Autónoma de Galicia. Dirección General de Medio Natural y Política Forestal, Ministerio de Medio Ambiente, Medio Rural y Marino, Madrid.

Montero González, G., 2018. Pinus pinaster Ait. Revista Foresta 72, 6-7.

Myers, R.H., 1990. Classical and Modern Regression with Applications, 2nd ed. Duxbury Press, Belmont, California.

Nanos, N., Tadesse, W., Montero, G., Gil, L., Alia, R., 2000. Modelling resin production distributions for *Pinus pinaster* Ait. using two probability functions. Ann. For. Sci. 57, 369–377.

Neis, F.A., de Costa, F., Füller, T.N., de Lima, J.C., Rodrigues-Corrêa, K.C.S., Fett, J.P., Fett-Neto, A.G., 2018. Biomass yield of resin in adult *Pinus elliottii* Engelm. trees is differentially regulated by environmental factors and biochemical effectors. Ind. Crops Prod. 118, 20–25.

Neis, F.A., de Costa, F., de Araújo Jr., A.T., Fett, J.P., Fett-Neto, A.G., 2019. Multiple industrial uses of non-wood pine products. Ind. Crops Prod. 130, 248–258.

Pinillos, F.M., Picardo, A., Allué-Andrade, M., 2009. La resina: Herramienta de conservación de nuestros pinares. Cesefor, Junta de Castilla y León, Fundación Biodiversidad, Soria, Spain.

Prada, M.A., Allué, M., Gil, L., Pardos, J.A., 1997. Programa de mejora genética de *Pinus pinaster* Ait. grandes productores de miera en la provincia de Segovia. Actas de la reunión de Madrid del grupo de trabajo de mejora genética forestal. Cuad. Soc. Esp. Cienc. For. 5, 67–71.

Rodrigues, K.C.S., Fett-Neto, A.G., 2009. Oleoresin yield of *Pinus elliottii* in a subtropical climate: Seasonal variation and effect of auxin and salicylic acid-based stimulant paste. Ind. Crops Prod. 30, 316–320.

Rodrigues, K.C.S., Azevedo, P.C.N., Sobreiro, L.E., Pelissari, P., Fett-Neto, A.G., 2008. Oleoresin yield of *Pinus elliottii* plantations in a subtropical climate: Effect of tree diameter, wound shape and concentration of active adjuvants in resin stimulating paste. Ind. Crops Prod. 27, 322–327.

Rodrigues-Corrêa, K.C.S., de Lima, J.C., Fett-Neto, A.G., 2013. Oleoresins from pine: production and industrial uses. In: Ramawat, K.G., Mérillon, J.M. (Eds.), Natural Products. Springer-Verlag, Berlin, pp. 4037–4060.

Rodríguez García, A., 2016. Factores Anatómicos, Dendrométricos y Climáticos Implicados en la Producción de Resina de *Pinus pinaster* Ait.: Aplicación a la Mejora de Los Métodos de Resinación (Doctoral Thesis). E.T.S.I. Montes, Universidad Politécnica de Madrid, Madrid, Spain.

Rodríguez-García, A., López, R., Martín, J.A., Pinillos, F., Gil, L., 2014. Resin yield in *Pinus pinaster* is related to tree dendrometry, stand density and tapping-induced systemic changes in xylem anatomy. For. Ecol. Manag. 313, 47–54.

Rodríguez-García, A., Martín, J.A., López, R., Mutke, S., Pinillos, F., Gil, L., 2015. Influence of climate variables on resin yield and secretory structures in tapped *Pinus pinaster* Ait. in central Spain. Agric. For. Meteorol. 202, 83–93.

Rodríguez-García, A., Martín, J.A., López, R., Sanz, A., Gil, L., 2016. Effect of four tapping methods on anatomical traits and resin yield in Maritime pine (*Pinus pinaster* Ait.). Ind. Crops Prod. 86, 143–154.

Ruel, J.J., Ayres, M.P., Lorio, P.L., 1998. Loblolly pine responds to mechanical wounding with increased resin flow. Can. J. For. Res 28, 596–602.

SAS Institute Inc., 2014. SAS® 9.4 User's Guide. SAS Institute Inc., Cary, NC, USA.

Schopmeyer, C.S., Larson, P.R., 1955. Effects of diameter, crown ratio, and growth rate on gum yields of slash and longleaf pine. J. For. 53, 822–826.

Siipilehto, J., Mehtätalo, L., 2013. Parameter recovery vs. parameter prediction for the Weibull distribution validated for Scots pine stands in Finland. Silva Fenn. 47 (4), 1057.

Soliño, M., Yu, T., Alía, R., Auñón, F., Bravo-Oviedo, A., Chambel, M.R., de Miguel, J., del Río, M., Justes, A., Martínez-Jauregui, M., Montero, G., Mutke, S., Ruiz-Peinado, R., García del Barrio, J.M., 2018. Resin-tapped pine forests in Spain: ecological diversity and economic valuation. Sci. Total Environ. 625, 1146–1155.

Zas, R., Quiroga, R., Touza, R., Vázquez-González, C., Sampedro, L., Lema, M., 2020a. Resin tapping potential of Atlantic maritime pine forests depends on tree age and timing of tapping. Ind. Crops Prod. 157, 112940.

Zas, R., Touza, R., Sampedro, L., Lario, F.J., Bustingorri, G., Lema, M., 2020b. Variation in resin flow among Maritime pine populations: Relationship with growth potential and climatic responses. For. Ecol. Manag. 474, 118351.