

Article

Estimating Forest Variables for Major Commercial Timber Plantations in Northern Spain Using Sentinel-2 and Ancillary Data

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Abstract: In this study, we used Spanish National Forest Inventory (SNFI) data, Sentinel-2 imagery and ancillary data to develop models that estimate forest variables for major commercial timber plantations in northern Spain. We carried out the analysis in two stages. In the first stage, we considered plots with and without sub-meter geolocation, three pre-processing levels for the Sentinel-2 images and two machine learning algorithms. In most cases, geometrically, radiometrically, atmospherically and topographically (L2A-ATC) corrected images and the random forest algorithm provided the best results, with topographic correction producing a greater gain in model accuracy as the average slope of the plots increased. Our results did not show any clear impact of the geolocation accuracy of SNFI plots on results, suggesting that the usual geolocation accuracy of SNFI plots is adequate for developing forest models with data obtained from passive sensors. In the second stage, we used all plots together with L2A-ATC-corrected images to select five different groups of predictor variables in a cumulative process to determine the influence of each group of variables in the final RF model predictions. Yield variables produced the best fits, with R^2 ranging from 0.39 to 0.46 (RMSE% ranged from 44.6% to 61.9%). Although the Sentinel-2-based estimates obtained in this research are less precise than those previously obtained with Airborne Laser Scanning (ALS) data for the same species and region, they are unbiased (Bias% was always below 1%). Therefore, accurate estimates for one hectare are expected, as they are obtained by averaging the values of 100 pixels (model resolution of 10 m pixel^{-1}) with an expected error compensation. Moreover, the use of these models will overcome the temporal resolution problem associated with the previous ALS-based models and will enable annual updates of forest timber resource estimates to be obtained.

Keywords: remote sensing; optical sensor; national forest inventory; machine learning techniques; volume; biomass



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1. Introduction

The role of forest plantations in helping to tackle many of the great challenges of our time is increasingly recognized, as forests provide goods and services, generate jobs, sustain incomes and act as a source of food and fuel [1]. Moreover, new value-added products obtained from these forest resources (e.g., lignocellulosic biofuels, cellulose-based fibers such as viscose, and the multitude of valuable substances obtained from forest residues in biorefineries) indicate the increasing importance of forest plantations to society as alternative renewable sources for producing bioenergy, biochemicals and biomaterials [2]. Northern Spain (which encompasses the regions of Galicia, Asturias, Cantabria and the Basque Country) is one of the most productive forest areas in Europe and is covered by extensive plantations of maritime pine, radiata pine and Tasmanian blue gum. Thus, in the period 2005–2019, the average harvested volume of the three cited species reached

9,700,505 m³ year⁻¹, which represented 89.9% of the total volume harvested annually (TVHA) in the four regions and 63.3% of the TVHA in the whole of Spain [3]. These data highlight the great socioeconomic dimension of the forest plantations, which also provide other important ecosystem services, including wildlife refuge provision, climate change mitigation and hydrological regulation. Quantification of forest variables, particularly current timber stocks (in terms of volume, biomass or carbon), and of their distribution and temporal variation over the territory, is therefore essential to facilitate planning for landowners, enterprises, forest managers and researchers.

Evaluation of forest resources has traditionally been based on measurement of the diameter at breast height and total height of the trees in numerous plots (direct method), and remains to be the most common method for estimating forest stocks [4]. Although this method is accurate, it is expensive, time-consuming and presents operational problems as it can only be applied to small areas [5]. However, the plot-level data can also be used as “training data” to develop forest models based on variables determined by remote sensing (indirect method) [6].

The combined use of public databases (e.g., the National Forest Inventory, NFI) and the semi-automatic capture of state variables by various remote sensing techniques has enabled these problems to be overcome and forest models to be developed without the need for fieldwork [7]. In fact, timber stock quantification is currently one of the most common applications of remote sensing (RS) and thus supports sustainable forest management, as RS provides reliable data and overcomes the two aforementioned limitations of traditional methods (data scarcity and operational problems), providing estimates even in areas not previously sampled [8].

Depending on whether the energy to which the sensors respond is internal or external to the system, remote sensing can be classified into two groups: (i) active and (ii) passive. In the first group, the sensor emits energy and then detects and measures the energy reflected from the target, while in the second, the sensor measures the external solar energy reflected from the Earth’s surface (surface reflectance or reflectance) [9] using optical multispectral or hyperspectral sensors. Airborne Laser Scanning (ALS) (also referred to as LiDAR: Light Detection and Ranging) and, to a lesser extent, RADAR (Radio Detection and Ranging) are the active sensing methods most commonly used for forestry applications. Active sensors can penetrate the forest canopy and do not depend on weather, cloud or lighting conditions [10]. As a result of their greater accuracy and higher spatial resolution, these types of sensors are frequently used to study the vertical structure of forests [11,12] and timber volume or biomass (e.g., [13,14]). However, they provide predictions with low temporal resolution. Since 2008, Spain has had available a national ALS coverage compiled by the PNOA-LiDAR project of the Instituto Geográfico Nacional (IGN) [15]. Although this database is very valuable for forestry purposes, it has several drawbacks: (i) low temporal resolution and (ii) different data acquisition depending on the region. Although the temporal resolution of the ALS data is officially 5 years, delays often occur, leading to intervals of up to 8 years in some regions (e.g., Asturias 1st coverage 2012 and 2nd in 2020). With such long intervals, forest stock estimation quickly becomes out of date because the species used are fast growing and also because of the occurrence of abiotic/biotic damage, forest fires and forestry management actions (clearcutting or thinning). Different rates of data acquisition in different regions also generate problems associated with lack of harmonization when building models for several nearby regions [14].

These two drawbacks of ALS data can be overcome by using passively, remotely sensed data with very high temporal resolution. Although data from passive sensors are limited by cloud cover, the short revisit period of satellites increasingly facilitates production of cloud-free mosaics, even within short periods of time [16].

The free availability of remotely sensed data (e.g., Landsat, MODIS or Sentinel) has led to a great increase in the use of this type of data in the last decade for estimating several forest variables such as growing stock volume [4,17], biomass [18,19], forest cover [16,20] and forest changes [21]. The Sentinel-2A and Sentinel-2B satellites, launched by the Euro-

pean Space Agency (ESA) through its Copernicus program in 2015 (S2A) and 2017 (S2B), have a temporal resolution of five days, and the imagery includes 13 spectral bands with a spatial resolution ranging from 10, 20 and 60 m/pixel depending on the band [22]. The high levels of temporal and spatial resolution have enabled estimation of forest variables with sufficient spatial detail for forest inventories and sustainable forest management purposes [17] and have made these images a popular source of remotely sensed data for forestry research in recent years [23].

Public databases such as National Forest Inventories (NFIs) include information about key forest variables (structure, growth and yield) and provide the field data necessary to construct wall-to-wall spatial models to predict forest variables using remote sensing data as independent variables. However, the major problems associated with the combined use of NFI and remotely sensed data are the temporal mismatches and the low positioning accuracy of the NFI field plots that sometimes occur. The first is not a problem when using optical data from Sentinel-2, Landsat-8 or MODIS because of the high temporal resolution of these sensors. However, the second has been recognized to have important effects on forest variable estimation, mainly when dealing with LiDAR data [24]. This has led researchers to adopt different approaches in an attempt to mitigate the effects (e.g., [4,14,25]).

Both parametric and nonparametric models have frequently been used to derive forest stock variables from remotely sensed data (e.g., [18,26]). The main advantages of parametric linear models are their simplicity and clarity, while the main drawbacks are the probability of selecting highly correlated predictors with little physical justification and the nonfulfilment of the assumptions of normality, homoscedasticity, independence and linearity [27]. Unlike linear models, machine learning algorithms can learn highly complex nonlinear relationships, integrate multiple factors and thus obtain better simulation results [10]. However, the resulting models are usually complex, and the role of the variables selected from the models may be difficult to understand [28].

In this study, we evaluated the use of multispectral Sentinel-2 imagery to solve the problem of low temporality in previous models obtained from ALS data for the same species in northern Spain. The main objective of this study was to generate, for major commercial timber plantations in northern Spain, a high-resolution raster database with information about key forest variables based on Sentinel-2 images. To fulfil the main objective, the specific objectives were as follows: (i) generation of a high-resolution raster database including the independent variables considered in this study; (ii) testing the effect on predictions of implementing different image correction levels and/or plot geolocation accuracy and by using different categories of independent variables; (iii) selection of the best empirical model by comparing two well-known nonparametric machine learning regression techniques; and (iv) use of the best approach to generate a high-resolution raster database including key forest variables.

2. Materials and Methods

2.1. Study Area

This study was conducted in the four most productive forest regions in Spain (Galicia, Asturias, Cantabria and the Basque Country), which cover a total area of 52,821.44 km². Most of this area is included in the European Atlantic Bio-Geographical Region [29] (Figure 1), which is characterized by mild temperatures (mean annual temperatures varying between 11.5 °C and 14.5 °C) and precipitation that is quite uniformly distributed throughout the year and is often more than 1000 mm per year [30]. These favorable climatic conditions make this area very important for forestry in Spain. Forests occupy an area of 25,158 km² [31] in the study region, representing 47.6% of the total surface area. The landscape is complex, and the different combinations of topographic variables and landform strongly influence the type and vigor of the vegetation communities. Considering the area occupied, *Eucalyptus globulus* is the dominant forest species (22.5%), followed by *Pinus pinaster* (20.2%), *Quercus robur* (15.5%), *Quercus pyrenaica* (8%), *Castanea sativa* (8%), *Pinus radiata* (7.5%) and *Fagus sylvatica* (5.7%) [32].

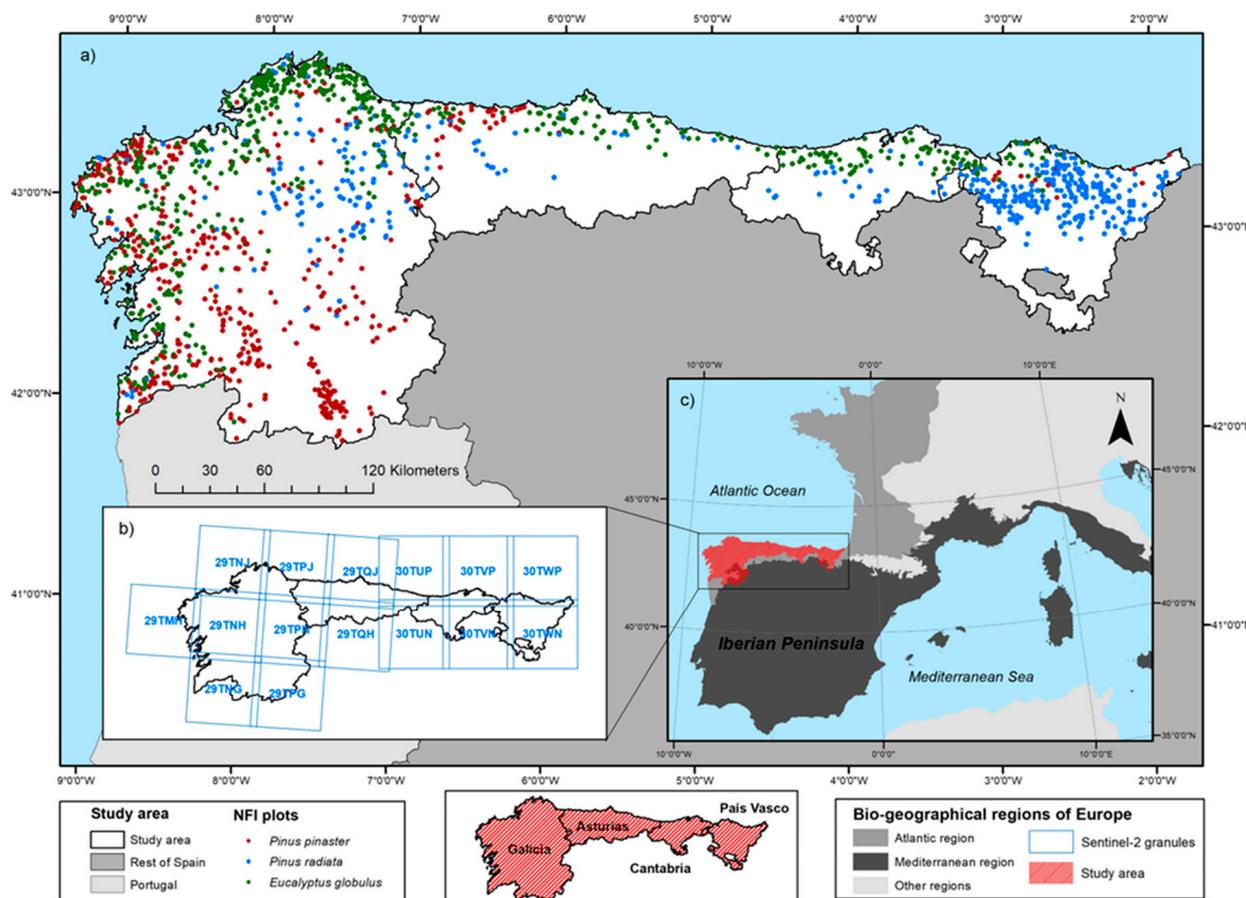


Figure 1. Overview of (a) location of the study area including the Spanish National Forest Inventory plots used in this study, (b) Sentinel-2 granules of the study area, and (c) European bio-geographical regions in northern Spain.

2.2. Data Collection and Pre-Processing

Four different types of data were used to develop the wall-to-wall remote sensed-based forest models: (i) field data; (ii) remotely sensed data; (iii) terrain data; and (iv) climatic data.

2.2.1. Field Data

The field plot data used in this study were obtained from the Spanish National Forest Inventory (SNFI) conducted by the Spanish Ministry of Agriculture, Fishing and Food [32]. The SNFI operates on a ten-year cycle, except for more productive forest species in northern Spain, for which a five-year cycle is used. We used the data from the last update of this inventory (SNFI 4.5), which was conducted in 2018 for the three most productive forest species in the study region: Tasmanian blue gum (*E. globulus*), maritime pine (*P. pinaster*) and radiata pine (*P. radiata*). In this inventory, the sampling plots are located at the intersections of a 1×1 km UTM grid comprising four concentric subplots of radius of 5, 10, 15 and 25 m, with a minimum diameter at 1.3 m aboveground level and thresholds of 75, 125, 225 and 425 mm, respectively [33].

Although the SNFI initially did not provide accurate coordinates, new remote sensing techniques have demonstrated the need for accurate coordinates [34] when using SNFI data to develop wall-to-wall forest models. The plot positioning of the fourth SNFI has an expected average theoretical accuracy of approximately 3–5 m [35], although the errors will actually be much greater in practice [14]. This led to the SNFI to capture new coordinates with errors less than 1 m in 73.36% of the plots in last remeasurement in 2018 (SNFI 4.5), making it easier to combine the field plot data with the information provided

by remote sensing systems [36]. We therefore had available plots with low and high geolocation accuracy.

Plots of the three planted species of interest were established in pure stands (basal area 80% of the total basal area within the plot). Following this criterion, a total of 1471 plots within the study area were available for analysis. Among these plots, 589 were dominated by *E. globulus*, 474 by *P. pinaster* and 408 by *P. radiata*. Forest state variables such as the number of stems per hectare (N), basal area (G), dominant height (H_0), total over bark volume (TV) and aboveground biomass (AGB) were calculated from tree variable measurements and by using appropriate expansion factors. Stand-level species-specific allometric models developed for the same ecoregion by [37] were used to estimate aboveground biomass per plot. Table 1 summarizes the descriptive statistics of the stand-related yield variables considered for the three forest species in the study area.

Table 1. Descriptive statistics of the dependent variables analyzed in this study (number of stems per hectare, N ; basal area, G ; dominant height, H_0 ; total over bark volume, TV ; and total aboveground biomass, AGB) extracted from the SNFI-4.5 plots where dominant species basal area was equal to or greater than 80% of the total basal area.

Species	No. Plots	Forest Variable	Descriptive Statistic			
			Mean	Min.	Max.	Std.
<i>E. globulus</i>	589	N (stems ha ⁻¹)	833.83	10.19	2695.02	499.93
		G (m ² ha ⁻¹)	18.30	0.44	52.25	0.44
		H_0 (m)	21.43	6.70	43.55	7.26
		TV (m ³ ha ⁻¹)	148.42	0.68	522.67	118.14
		AGB (Mg ha ⁻¹)	99.44	0.98	371.55	81.68
<i>P. pinaster</i>	474	N (stems ha ⁻¹)	574.60	10.19	3176.03	439.15
		G (m ² ha ⁻¹)	22.60	0.42	55.73	13.70
		H_0 (m)	16.67	3.40	31.78	6.34
		TV (m ³ ha ⁻¹)	164.05	0.88	460.72	119.37
		AGB (Mg ha ⁻¹)	92.26	0.80	298.64	68.25
<i>P. radiata</i>	408	N (stems ha ⁻¹)	453.66	25.46	1773.48	294.07
		G (m ² ha ⁻¹)	27.82	0.67	66.62	13.54
		H_0 (m)	22.55	5.70	39.55	6.28
		TV (m ³ ha ⁻¹)	246.23	2.25	699.31	147.64
		AGB (Mg ha ⁻¹)	127.43	1.59	356.93	75.38

The distribution of the species under study and classification of vegetation types were determined using the Spanish Forest Map (Figure 1) (scale 1:25,000, minimum mapping unit of 1 ha), developed in coordination with SNFI-4.5.

2.2.2. Sentinel-2 Remote Sensing Data

We used freely available multispectral Sentinel-2 satellite (two twin-polar orbiting satellites) images, downloaded from the Copernicus Open Access Hub (<https://dataspace.copernicus.eu/>, accessed on 21 December 2023). These images were subjected to several corrections, and different spectral bands, indices and texture features were selected as independent remotely sensed variables for the present study (see Figure 2 for details of the workflow).

Image Pre-Processing Levels and Spectral Bands

Sentinel-2 data are available in different processed forms. The images we used were obtained in Level-1C product format (TOA, Top-Of-Atmosphere reflectance in cartographic geometry) in UTM/WGS84 projection and with less than 10% cloud cover. The Level-1C processing includes geometric corrections, radiometric processing and mask generation. After implementing atmospheric and topographic corrections with the Sen2Cor 2.8 tool [38], the Level-1C images were converted to Level-2A Bottom-Of-Atmosphere (BOA) reflectance

images. To implement the corrections with Sen2Cor 2.8 tool, we used a digital elevation model (DEM) of 5 m of spatial resolution, developed in Spain by the National Center for Geographic Information (CNIG). The study area includes mountainous areas with sloping terrain, and topographic corrections of images may therefore play an important role. In this case, we used a bidirectional reflectance distribution function (BRDF) correction for vegetated mountainous with the recommended standard by ESA [39]. This correction is not available to download in the official ESA repository and must be generated by users. We therefore considered three pre-processing levels for the Sentinel images: (i) level L1C, scenes with geometric and radiometric corrections; (ii) level L2A-AC, scenes with geometric, radiometric and atmospheric corrections; and (iii) level L2A-ATC, scenes with geometric, radiometric, atmospheric and topographic corrections (for more information about Sentinel product types, see <https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-2-msi/products-algorithms/>, accessed on 21 December 2023, and [40]).

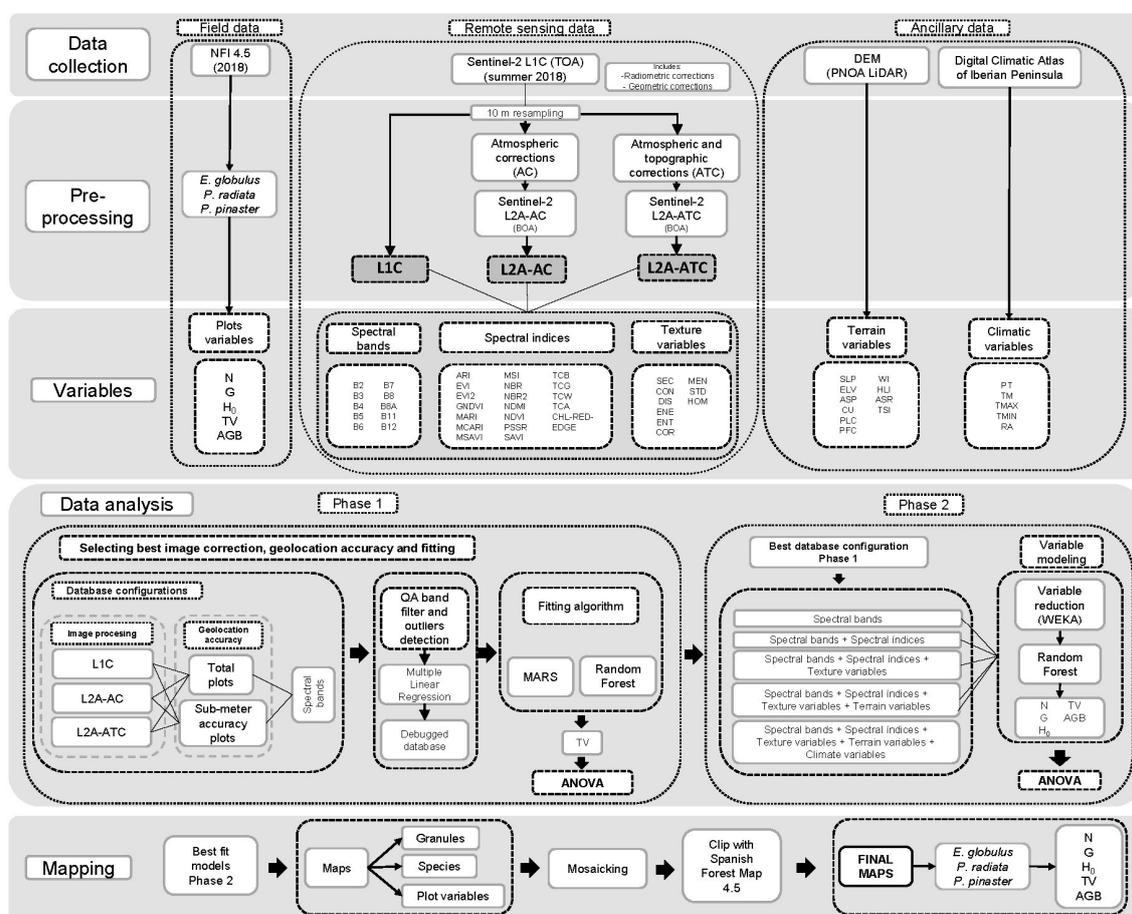


Figure 2. Workflow adopted in this study for modelling and mapping forest stock variables through Sentinel-2 data and ancillary variables.

On the other hand, the Sentinel-2 Level-2A product enables masking different types of pixels at 20 and 60 m resolution by merging the information obtained from cirrus cloud detection and cloud shadow detection. For this study, we only used the pixels classified as vegetation (scene classification label = 4; more information available in <https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-2-msi/level-2a/algorithm-overview/>, accessed on 21 December 2023).

The satellite imagery was acquired between 14 June and 27 August 2018 (i.e., the same year that the field sampling was carried out), with fifteen tiles being necessary to cover the region of interest in northern Spain. A brief description of the images used is given in Table 2.

Table 2. Acquisition dates and solar angles of fifteen Sentinel-2 scenes.

Satellite/Granule	Acquisition Date	Solar Zenith (°)	Solar Azimuth (°)
S2A/29TMH	11 August 2018	30.86	148.82
S2A/29TNG	19 June 2018	22.94	138.83
S2A/29TNH	11 August 2018	30.42	150.94
S2A/29TNJ	11 August 2018	31.22	151.58
S2A/29TPG	19 June 2018	22.36	141.25
S2B/29TPH	14 June 2018	23.10	143.23
S2B/29TPJ	24 June 2018	23.95	143.16
S2B/29TQH	24 June 2018	22.67	144.43
S2B/29TQJ	24 June 2018	23.41	145.61
S2A/30TUN	5 August 2018	29.46	146.64
S2A/30TUP	5 August 2018	30.25	147.34
S2A/30TVN	5 August 2018	29.00	148.81
S2A/30TVP	5 August 2018	29.80	149.51
S2B/30TWN	27 August 2018	35.52	153.22
S2B/30TWP	27 August 2018	36.34	153.70

All bands with 10 and 20 m spatial resolution were selected for inclusion in the classification procedure, but the spatial resolution of the 20 m bands was later increased to 10 m by using the nearest neighbor resampling method (Table 3).

Table 3. Description of the ten Sentinel-2 bands used in this study.

Band	Symbol	Spectral Region	Wavelength (µm)	Spatial Resolution (m)
Band 2	B2	Blue	0.46–0.52	10
Band 3	B3	Green	0.54–0.58	10
Band 4	B4	Red	0.65–0.68	10
Band 5	B5	Red-Edge-1 (RE1)	0.70–0.71	20
Band 6	B6	Red-Edge-2 (RE2)	0.73–0.75	20
Band 7	B7	Red-Edge-3 (RE3)	0.76–0.78	20
Band 8	B8	Near-Infrared (NIR)	0.78–0.90	10
Band 8A	B8A	Narrow NIR (nNIR)	0.85–0.87	20
Band 11	B11	Shortwave infrared (SWIR-1)	1.56–1.65	20
Band 12	B12	Shortwave infrared (SWIR-2)	2.10–2.28	20

Spectral Indices

Spectral indices are simple numerical indicators that reduce multispectral (two or more spectral bands) data to a single variable for predicting and assessing vegetation characteristics, which is why they are also known as vegetation indices [41]. The high spectral resolution of Sentinel-2 imagery enables extraction of different indices from the spectral bands. Thus, 19 spectral indices were derived from the Sentinel-2 bands and the resultant quality scene classification band for each Sentinel-2 scene. These spectral indices are shown in Table 4, and the formulation used can be consulted in Supplementary Material (Table S1).

Texture Variables

Textural variables are used to try to explain different relationships between object pixel and neighboring pixels, although the results are influenced by window size and directions [42]. If the window size is small, the differences within the kernel can often be exaggerated, increasing the noise content in the texture image. With a larger window size, the sample size increases, thus smoothing the textural variation and leading to relevant information about the texture being overlooked [43]. Different authors have tested different window sizes and directions (e.g., [42,44]). Window sizes of 7×7 or less and directions of 90 degrees have been found to be successful, as they enable the differences between the

pixels occupied by trees and the ground to be captured while minimizing noise [45]. We used an optimized window size of a kernel 7×7 m to calculate 10 textural features derived from the derived from the Normalized Difference Vegetation Index (NDVI) using the Grey Level Co-occurrence Matrix (GLCM) texture extraction method [46] in the Sentinels Application Platform 9.0.0 (SNAP) software, which can be found at <https://step.esa.int/main/download/snap-download/>, accessed on 21 December 2023. The use of texture variables derived from spectral data has yielded satisfactory results in forest variables estimation (e.g., [44,47,48]).

Table 4. Characteristics considered as candidate independent variables of the forest models.

Group	Variable Name
Spectral bands	Band 2—Blue (B2), Band 3—Green (B3), Band 4—Red (B4), Band 5—Vegetation Red-Edge-1 (B5), Band 6—Vegetation Red-Edge-2 (B6), Band 7—Vegetation Red-Edge-3 (B7), Band 8—NIR (B8), Band 8A—Narrow NIR (B8A), Band 11—SWIR-1 (B11), Band 12—SWIR-2 (B12).
Spectral indices	Anthocyanin Reflectance Index (ARI), Chlorophyll Red-Edge (CRE), Enhanced Vegetation Index (EVI), Enhanced Vegetation Index 2 (EVI2), Green Normalized Difference Vegetation Index (GNDVI), Modified Anthocyanin Reflectance Index (MARI), Modified Chlorophyll Absorption in Reflectance Index (MCARI), Modified Soil Adjusted Vegetation Index (MSAVI), Modified Soil Adjusted Vegetation Index (MSI), Normalized Burn Ratio (NBR), Normalized Burn Ratio 2 (NBR2), Normalized Difference Moisture Index (NDMI), Normalized Difference Vegetation Index (NDVI), Pigment-Specific Simple Ratio (PSSR), Soil Adjusted Vegetation Index (SAVI), Tasseled Cap Angle (TCA), Tasseled Cap Brightness (TCB), Tasseled Cap Greenness (TCG), Tasseled Cap Wetness (TCW).
Texture	Angular Second Moment (SEC), Contrast (CON), Correlation (COR), Dissimilarity (DIS), Energy (ENE), Entropy (ENT), Homogeneity (HOM), Max (MAX), Mean (MEN), Standard Deviation (STD).
Terrain	Aspect (ASP), Aspect/Slope Ratio (ASR), Curvature (CU), Elevation (ELV), Heat Load Index (HLI), Plan Curvature (PLC), Profile curvature (PFC), Slope (SLP), Terrain Shape Index (TSI), Wetness Index (WI).
Climatic	Average Temperature (TM), Maximum Temperature (TMAX), Minimum Temperature (TMIN), Precipitation (PT), Radiation (RA).

Finally, as result of the Sentinel-2 image information extraction process, we recorded 39 layers (10 spectral bands + 19 spectral indices + 10 texture features) for each Sentinel-2 scene (Table 4). As previously commented, these 39 layers were available at three pre-processing levels: (i) level L1C (scenes with geometric and radiometric correction); (ii) level L2A-AC (scenes with geometric, radiometric and atmospheric corrections); and (iii) level L2A-ATC (scenes with geometric, radiometric, atmospheric and topographic corrections).

2.2.3. Ancillary Data

Two types of auxiliary variables were considered in this study: terrain and climatic variables.

Terrain Variables

To support the terrain analysis, a digital elevation model (DEM) of spatial resolution 5 m, developed by the Spanish National Center for Geographic Information (CNIG), was obtained. This model is available for free download at <http://centrodedescargas.cnig.es/CentroDescargas/>, accessed on 21 December 2023. We derived 10 terrain variables from the DEM of the CNIG as the average value of pixels inside each sample plot (see Table 4). This was resampled to 10 m/pixel resolution using the cubic convolution resampling method. Terrain variables are important and influence trees distribution, growth and yield [49], which is why we also included these variables with the aim of assessing their contribution for improving predictions of forest variables. The variables were generated using ArcGIS 10.8 software [50], which was selected on the basis of its wide use in previous studies (e.g., [18]).

Climatic Variables

Five climate variables were obtained for each pixel of 200 m spatial resolution (Table 4) from the Digital Climatic Atlas of the Iberian Peninsula [51]. This atlas is published on the internet at <https://opengis.grumets.cat/wms/iberia/index.htm>, accessed on 21 December 2023. The variables were resampled to 10 m/pixel using the nearest neighbor resampling method applied here. Solar radiation, temperature and precipitation variables drive plant growth and water availability in forest ecosystems. It is therefore reasonable to use the climatic features as independent variables when building the models. Moreover, within the framework of uncertain global climate change, production of different forest ecosystems may vary in the coming decades. The inclusion of climatic variables as independent variables in the models may enable comparison of different estimates obtained in the future.

2.3. Data Analysis, Model Fitting and Evaluation

2.3.1. Data Analysis

As the final result of the “Data collection and pre-processing” stage of this study, we had available a set of 54 variables (grouped in five groups) as candidate independent variables to be included in the models for predicting forest variables for three major commercial timber plantations in northern Spain. Data analysis was accomplished in two different phases (see Figure 2).

Analysis in Phase 1

This phase consisted of outlier analysis and subsequent selection of the best option from among the different levels of three qualitative factors: image correction, geolocation accuracy and algorithm fitting. The first step was the outlier detection caused by various factors, such as sensor errors, atmospheric interference, cloud cover, shadows, or land cover changes, and data debugging process, which consisted of the following sub-steps for each forest species: (i) applying the vegetation classification mask derived from Sentinel-2 Level-2A product; (ii) fitting a multilinear model to the dependent variable (*TV*) with the spectral bands as independent variables (10 variables); (iii) use of the stepwise regression method to eliminate the independent variables (of the 10 considered) that do not contribute to the model, (iv) fitting a multilinear model to the dependent variable (*TV*) with the remaining independent variables, and (v) plotting studentized residuals against leverage to detect outliers and/or observations with high leverage and extract these outliers to debug the database. To carry out this process, we used the R library, Tools for Building OLS Regression Models (*olsrr*) in R 4.0 statistical software (<https://cran.r-project.org/>, accessed on 21 December 2023). We used *TV* as a dependent variable in phase 1 of the analysis as it is usually the most important variable from the point of view of estimating forest resources.

After the data debugging process, a database was generated for each forest species (*E. globulus*, *P. pinaster* and *P. radiata*) considering three different levels of image processing (L1C, L2A-AC and L2A-ATC), two levels of plot geolocation accuracy (all plots and only sub-meter geolocation plots). This database was fitted to total over bark volume (*TV*) using two different algorithms, Random Forest (RF) and Multivariate Adaptive Regression Splines (MARS), with the spectral bands as independent variables. We used the total over bark volume (*TV*) as a dependent variable (it is currently the most important forest yield variable) with the sole aim of choosing the best alternative.

Separate one-way analysis of variance (ANOVA) was performed for the *TV* response variable, to test the effect of the different factors considered (image correction, plot geolocation accuracy and fitting algorithm), regardless of the species. Tukey’s honestly significant difference (HSD) multiple range test was used to determine homogeneous groups according to the similarity of the root mean square error (RMSE).

Analysis in Phase 2

After selecting the best image correction, geolocation accuracy and fitting techniques, we proceeded to the second phase of the data analysis (see Figure 2). This consisted of

selecting five different groups of predictor variables in a cumulative process to determine the influence or importance of each group of variables in the final prediction. The following groups of predictor variables were considered:

1. Spectral bands.
2. Spectral bands + spectral indices.
3. Spectral bands + spectral indices + texture variables.
4. Spectral bands + spectral indices + texture variables + terrain variables.
5. Spectral bands + spectral indices + texture variables + terrain variables + climatic variables.

We also performed ANOVA for each forest response variable (N , G , H_0 , TV and AGB) and forest species, in order to test the contribution of each of the five different groups of predictors to the response variable. Tukey's HSD multiple range test was used to determine homogeneous groups according to the similarity of the RMSE.

2.3.2. Modelling Techniques

In the past, quantitative predictions of most forest variables by means of remote sensing have involved traditional parametric regression techniques (e.g., [52–54]). However, this may not be suitable for analysis involving a potentially large number of predictors with complex interactions [55], as when dealing with remote sensing data. In the last few decades, the popularity of nonparametric methods has increased greatly for several reasons: (i) the speed and ease of implementation; (ii) the absence of restrictive assumptions; and (iii) the ability of some methods to include categorical dependent and (or) independent variables [54]. Among the numerous nonparametric techniques, we selected two widely used techniques for comparison: Random Forest and Multivariate Adaptive Regression Splines.

Random Forest (RF) regression techniques, first proposed by [56], are nonparametric techniques consisting of an ensemble of decision trees. This algorithm can be used for classification and regression and has been widely used in this type of research (e.g., [10,54,57–59]). In this technique, different independent variables, from the total set, are randomly selected to develop numerous decision trees. With randomized sampling, the accuracy and stability are improved relative to a single decision tree approach [60]. When RF is used in regression, the final value for each sample is given by the weighted average obtained from the estimates of individual trees [56]. The user can select the number of stems and the independent variables (predictors) used to configure the algorithm. This nonparametric approach is not greatly influenced by the number of input data or the multicollinearity of the data [61].

Multivariate Adaptive Regression Splines (MARS), a well-known nonparametric technique first proposed by [62], provides very good results for estimating forest variables from remote sensing data (e.g., [26,63,64]). MARS enables modelling a target variable based on multiple predictor variables using splines. A spline is a curve that can be fixed at different points or knots, where the relationship between the target variable and the independent variables changes. It thus generates piece-wise linear models in the distinct intervals of the predictor variables. MARS finds the end points of these intervals in two steps, by first overfitting the model with more knots than required and then removing the knots that contribute least to the overall model fit. Hence, regression splines are continuous smooth functions that fit the distribution of the data. However, MARS has various drawbacks: its functions tend to overfit with input data, and parameter choice is complicated and may require several iterations to find the best combination [55].

2.3.3. Model Assessment and Evaluation

Repeated 10-fold cross-validation was used to evaluate the models. The data are first split into k folds (groups) of the same size. One group is then selected as test data and the $k-1$ fold is used to adjust the model, and the goodness-of-fit statistics is calculated for this k -fold. This process was repeated k times using all k -folds as test folds. Finally, when the k -fold cross-validation was completed, we repeated the whole process 10 times, which

is why it is named “repeated k-fold cross-validation”. Finally, the overall goodness-of-fit statistics were calculated as the average test statistics from 100 model runs (i.e., 10-fold cross-validation repeated 10 times using the training data).

The use of this validation technique is supported by various authors (e.g., [14,65]), although if the plot dataset is small, the use of this approach can have negative results [66].

Model performance was evaluated with several goodness-of-fit criteria, including the pseudocoeficient of determination (R^2), the bias (Bias), the root mean square error (RMSE) and the relative values of these (Bias% and RMSE%).

The variable importance measure (VIM) was used to guide selection of predictors for the final models. To ensure that values of variable importance were expressed on comparable scales, the VIM values were normalized so that they summed to a unit value (normalized importance, $VIM_N = (VIM - VIM_{min}) / (VIM_{max} - VIM_{min})$) and were also expressed in relative values (relative importance, $VIM_R = VIM / \sum VIM$).

R statistical software [67] was used to implement the techniques compared in this study and to carry out Tukey’s HSD multiple comparison test.

2.4. Deriving Raster Maps

The models finally selected, for each species and forest state variable, were applied to the surface that each species occupies (areas greater or equal to 80%), according to the Spanish Forest Map 4.5, to generate spatially continuous maps with a spatial resolution of 10 m/pixel. Finally, applying the best algorithm, we obtained 15 maps, one for each of the five target variables of each species.

3. Results

As previously commented and shown in Figure 2, the results were obtained in two separate phases.

3.1. Phase 1: Best Data Configuration and Fitting Technique

Extraction of outliers to debug the database by applying the vegetation classification mask and using the plots of studentized residues against leverage enabled elimination of between approximately 5.88 and 13.29% of the plots for each configuration. The *P. pinaster* plots of the L1C level were the most refined, with removal of 13.29% as outliers, and the least refined were *P. radiata* plots of the L1C and L2A-AC level, with removal of 5.88% as outliers (Table 5).

Table 5. Number of outliers for each dataset configuration.

Species	<i>E. globulus</i>			<i>P. pinaster</i>			<i>P. radiata</i>			
	Image Correction	L1C	L2A-AC	L2A-ATC	L1C	L2A-AC	L2A-ATC	L1C	L2A-AC	L2A-ATC
Total plots		589	589	589	474	474	474	408	408	408
Outliers		13 + 32	13 + 32	13 + 32	36 + 27	36 + 26	36 + 23	4 + 20	4 + 20	4 + 23
% Outliers		7.64	7.64	7.64	13.29	13.08	12.44	5.88	5.88	6.61

where outliers = plots removed from the application of vegetation classification mask + detection of influential observations from residuals vs. leverage plots.

According to the above criteria, from a total of 1471 plots within the study area, 1343 were finally available for analysis after applying the vegetation classification mask derived from Sentinel-2 Level-2A product and then removing influential observations from residuals vs. leverage plots (8.7%). Of these plots, 544 were dominated by *E. globulus*, 415 by *P. pinaster* and 384 by *P. radiata*.

After outlier detection and elimination, we had available for analysis a database of forest species which considered three different images processing levels, two different levels of plot geolocation accuracy and two model fitting algorithms. At this phase, as we were not building the final models, and to facilitate presentation of the results, we only

used the most important yield variable, i.e., total over bark volume (*TV*), as a dependent variable to select the best alternative. These data configuration enabled (i) selection of the best image processing level, (ii) assessment of the effect of the quality of plot geolocation and (iii) selection of the best-fitting algorithm. The results of this process are shown in Table 6.

Table 6. Summary of the goodness-of-fit statistics yielded by two regression algorithms (Multivariate Adaptive Regression Splines, (MARS) and Random Forest (RF)) for total over bark volume model (*TV*) and different image corrections and plot geolocation accuracy levels. All values represent the mean of 100 model runs (i.e., 10 replicates, each with 10-fold cross-validation).

Species	Image Correction	Geolocation Accuracy	No. Plot	R ²	Bias	MARS			R ²	Bias	RF	
						RMSE	RMSE%				RMSE	RMSE%
<i>E. globulus</i>	L1C	All plots	544	0.36	−0.40	96.98	64.18%	0.35	−1.35	97.66	64.63%	
		Sub-meter plots	457	0.34	−0.99	100.86	66.20%	0.34	−1.04	100.70	66.09%	
	L2A-AC	All plots	544	0.33	0.72	98.43	65.61%	0.29	−0.91	100.73	67.15%	
		Sub-meter plots	458	0.31	−0.07	102.37	67.91%	0.29	−0.75	103.50	68.66%	
	L2A-ATC	All plots	544	0.37	0.19	94.53	63.69%	0.42	−0.89	90.76	61.15%	
		Sub-meter plots	457	0.36	−0.32	97.49	65.45%	0.43	−0.59	91.11	61.17%	
<i>P. pinaster</i>	L1C	All plots	411	0.37	−0.44	95.89	58.04%	0.33	−1.05	98.22	59.45%	
		Sub-meter plots	351	0.38	−1.23	97.04	60.01%	0.37	1.10	97.09	60.03%	
	L2A-AC	All plots	412	0.38	0.32	95.48	57.94%	0.36	−2.13	96.79	58.74%	
		Sub-meter plots	353	0.39	0.40	96.24	59.55%	0.40	−2.28	94.84	58.69%	
	L2A-ATC	All plots	415	0.32	−0.42	99.72	60.79%	0.38	−1.18	94.97	57.89%	
		Sub-meter plots	354	0.37	0.22	98.04	60.78%	0.40	−1.29	94.55	58.62%	
<i>P. radiata</i>	L1C	All plots	384	0.24	0.76	132.90	52.96%	0.12	−1.10	142.91	56.95%	
		Sub-meter plots	172	0.24	−0.72	125.08	57.87%	0.09	−3.80	138.99	64.31%	
	L2A-AC	All plots	384	0.27	0.21	132.02	52.61%	0.14	−2.60	145.22	57.87%	
		Sub-meter plots	171	0.29	0.98	120.15	55.59%	0.11	−1.89	134.58	62.26%	
	L2A-ATC	All plots	381	0.36	0.54	119.82	48.66%	0.36	0.37	118.45	48.10%	
		Sub-meter plots	172	0.29	1.72	115.69	54.08%	0.26	−0.73	116.10	54.27%	

where L1C = scenes with geometric and radiometric correction; L2A-AC = scenes with geometric, radiometric and atmospheric corrections; and L2A-ATC = scenes with geometric, radiometric, atmospheric and topographic corrections. All plots = all plots are used after elimination of outliers; Sub-meter plots = only plots with sub-meter geolocation are used.

Our findings indicate that the performance of the fitting algorithm depended on the image correction level adopted. Thus, MARS was the best-fitting technique for L1C and L2A-AC image corrections levels, whereas RF was the best approach for the L2A-ATC image correction level. Therefore, we must consider both characteristics together to select the best alternative. Thus, in almost all cases, geometrically, radiometrically, atmospherically and topographically corrected images (L2A-ATC) and RF algorithm provided the best fits. These results led us to select the L2A-ATC image correction level and the RF algorithm to be considered in phase 2 of the analysis. This was true for all goodness-of-fit statistics, except for bias in two of the three results obtained for the different species (Table 6). We decided to select RF for further analysis in phase 2, although the bias values obtained must be considered with caution, as it is highly recommended that final model be unbiased or with the lowest possible bias. In fact, Tukey's HSD multiple comparison test produced significantly better results for the L2A-ATC correction level and the RF algorithm regardless of the species (Figure 3).

As we had available a proportion of plots where precise geolocation was guaranteed (sub-meter), we used two different databases to check the geolocation accuracy of the results: all plots and only plots with sub-meter geolocation. The goodness-of-fit statistics were used to compare both alternatives and the results obtained using the relative root mean square error for comparison purposes and considering the different image correction levels and the two algorithms used showed that the results for all the plots were higher (Table 6). In addition, Tukey's HSD multiple comparison test yielded very similar results (not significantly different) for the two levels of geolocation accuracy (Figure 3). Based on

these findings we decided to use the total number of plots to generate the final models in phase 2 of this study.

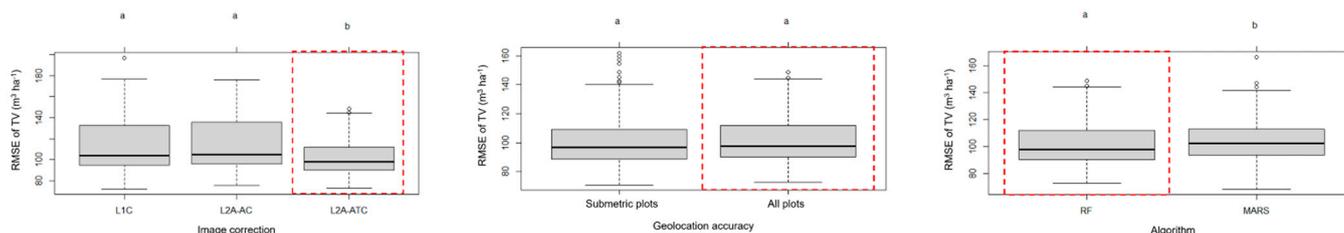


Figure 3. Results of Tukey's HSD multiple comparisons test for RMSE of the total over bark volume, TV ($m^3 ha^{-1}$) for three different levels of image correction (first column), for two levels of geolocation accuracy (second column) and for the two algorithms tested (third column). The same superscript letter beside values indicates that these are not significantly different, and different letters beside values indicate that these are significantly different ($p \leq 0.05$), where L1C = scenes with radiometric and geometric correction; L2A-AC = scenes with geometric, radiometric and atmospheric corrections; and L2A-ATC = scenes with geometric, radiometric, atmospheric and topographic corrections; RF = Random Forest; MARS = Multivariate Adaptive Regression Splines; TV = total over bark volume. The box-plot inserted in a rectangle outlined in red corresponds to the option selected as the best in each case.

Average increases in the relative root mean square error values ranged from 1.56% to 8.50% for comparison of the total over bark volume (TV) estimates for L2A-ATC correction with L1C-corrected images. The greatest improvement (8.50%) corresponded to *P. radiata*, stands of which generally grew on the steepest slope (average, 35.93%). By contrast, the lowest increment (1.56%) corresponded to *P. pinaster*, stands of which grew on less steep terrain (average slope, 23.76%) (Table 7).

Table 7. Relative root mean square error values yielded by the RF algorithm (see Table 8) for species and considering the average slope and aspect of the plots. Values within brackets indicate the percentage gain in RMSE relative to the L1C values.

Species		<i>E. globulus</i>	<i>P. pinaster</i>	<i>P. radiata</i>
Image correction	L1C	64.63%	59.45%	56.95%
	L2A-AC	67.15% (−2.51%)	58.74% (+0.72%)	57.87 (−0.92%)
	L2A-ATC	61.15% (+3.49%)	57.89% (+1.56%)	48.10 (+8.50%)
Plot variable	Average slope (%)	28.06	23.76	35.93
	Average aspect (°)	179.14	179.21	179.60
	% Plots with slope > 20%	67.91	52.95	75.74

Table 8. Comparison of the RF regression models for forest variables by species. Column (1) includes the value of the goodness-of-fit statistics using only spectral bands as predictors. The other columns show the percentage of change in the value of the statistics when using more predictor variables compared to (1). All values represent the mean of 100 model runs (i.e., 10 replicates, each with 10-fold cross-validation). The values highlighted in bold correspond to the data group selected as the best option for each combination of dependent variable and species.

Type	Dependent Variable	Statistic	<i>Eucalyptus globulus</i>					<i>Pinus pinaster</i>					<i>Pinus radiata</i>				
			Group of Predictor Variables					Group of Predictor Variables					Group of Predictor Variables				
			(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
Density	Number of stems, N (stems ha ⁻¹)	R ²	0.24	+4.17%	+8.33%	+8.33%	+8.33%	0.15	+6.67%	+26.67%	+40.00%	+53.33%	0.1	+20.00%	+60.00%	+80.00%	+50.00%
		Bias	4.64	+34.91%	+65.52%	+17.24%	+62.72%	-4.91	+61.30%	+102.85%	+92.26%	+178.00%	-6.02	-9.30%	+20.43%	+13.79%	+33.06%
		RMSE	438.49	-0.88%	-1.34%	-1.48%	-1.20%	412.04	-2.70%	-4.18%	-5.30%	-6.63%	283.12	-1.60%	-3.78%	-5.09%	-3.87%
	Basal area, G (m ² ha ⁻¹)	R ²	0.40	+10.00%	+12.50%	+15.00%	+15.00%	0.41	0.00%	+12.20%	+12.20%	+12.20%	0.33	0.00%	+9.09%	+18.18%	+18.18%
		Bias	-0.05	-20.00%	+20.00%	+40.00%	+80.00%	-0.08	-25.00%	-50.00%	-50.00%	+25.00%	-0.01	-300.00%	-500.00%	+100.00%	-500.00%
		RMSE	9.50	-3.26%	-3.68%	-4.63%	-4.42%	10.59	+0.38%	-4.53%	-4.25%	-4.72%	11.18	0.00%	-2.15%	-5.10%	-5.10%
Size	Dominant height, H_0 (m)	R ²	0.26	+3.85%	+11.54%	+23.08%	+26.92%	0.26	+7.69%	+7.69%	+34.62%	+42.31%	0.28	+14.29%	+21.43%	+32.14%	+28.57%
		Bias	0.04	-75.00%	-100.00%	-200.00%	-150.00%	-0.04	+50.00%	+50.00%	+100.00%	+25.00%	-0.01	+300.00%	-300.00%	-400.00%	-500.00%
		RMSE	6.31	-0.63%	-2.06%	-4.28%	-4.75%	5.49	-1.28%	-1.28%	-6.38%	-7.47%	5.36	-2.61%	-4.66%	-6.16%	-5.97%
	Total volume with bark, TV (m ³ ha ⁻¹)	R ²	0.41	+7.32%	+9.76%	+12.20%	+12.20%	0.38	+2.63%	+7.89%	+10.53%	+18.42%	0.37	+2.70%	+8.11%	+18.92%	+16.22%
		Bias	-0.62	+24.19%	+122.58%	+35.48%	+35.48%	-1.15	-45.22%	+20.00%	+37.39%	-11.30%	0.11	+254.55%	+618.18%	-27.27%	+218.18%
		RMSE	91.21	-3.03%	-3.66%	-4.14%	-4.14%	94.53	-1.03%	-2.84%	-3.09%	-5.11%	117.94	-1.09%	-2.42%	-5.27%	-4.58%
Yield	Aboveground Biomass, AGB (Mg ha ⁻¹) (Mg/ha)	R ²	0.41	+4.88%	+2.44%	+4.88%	+4.88%	0.36	+2.78%	+8.33%	+11.11%	+13.89%	0.35	+5.71%	+8.57%	+20.00%	+20.00%
		Bias	-0.79	+16.46%	+40.51%	+31.65%	+20.25%	-1.03	+2.91%	-27.18%	-35.92%	-35.92%	-0.41	-82.93%	-168.29%	-119.51%	-48.78%
		RMSE	63.13	-2.47%	-1.39%	-2.14%	-2.08%	54.88	-0.80%	-2.53%	-3.37%	-3.81%	61.15	-1.77%	-2.29%	-5.10%	-4.73%

where R² = pseudocoeficient of determination, Bias = bias, RMSE = root mean square error. (1) = spectral bands; (2) = spectral bands + spectral indices; (3) = spectral bands + spectral indices + texture variables; (4) = spectral bands + spectral indices + texture variables + terrain variables; (5) = spectral bands + spectral indices + texture variables + terrain variables + climatic variables.

3.2. Phase 2: Contribution of Each Group of Predictor Variables and Final Fitting Models

3.2.1. Contribution of Each Group of Predictor Variables

Analysis of the contribution of each of the five groups of predictor variables revealed differences according to the species. Thus, considering the results in Table 8 and the averaged results of the five forest models for each species shows that the contribution of spectral bands only (dataset 1) is higher for *E. globulus* ($R^2 = 0.34$) and decreases for *P. pinaster* ($R^2 = 0.31$) and *P. radiata* ($R^2 = 0.29$). Since the average performance of the final models for different species is quite similar, this implies a greater contribution of the other predictor variables for *P. pinaster* and *P. radiata*. Thus, for eucalypt, there is only an average increase in R^2 (considering the five dependent variables) of 13.47% for models fitted with the best dataset relative to dataset 1, whereas this increased to 28.03% and 26.59%, for maritime pine and radiata pine, respectively. For *E. globulus*, we observed a moderate-high contribution of spectral indices (group 1) and low contribution of textural (group 3) and terrain variables (group 4). Although textural and terrain variables make a large contribution for radiata pine and maritime pine, structural indices make a large contribution for radiata pine and a low contribution for maritime pine (Table 8).

The climatic variables (group 5) did not make valuable contributions to the eucalypt and radiata pine models. However, this group of variables improved the models for maritime pine. Looking closely at the *P. radiata* results, the contribution of climatic variables is null or negative as they reduce the predictive ability of the models (see Table 8). For this species, the group 4 variables contribute to the best forest variables prediction including the spectral bands, spectral indices, texture and terrain variables. Climatic variables improve the models for *P. pinaster*, increasing the pseudocoeficient of determination up to 13.33% (6.34% on average) relative to the results obtained from the group of variables no. 4 (without climatic variables). This contribution was only negligible for the basal area model (Table 8). Although these are important improvements, according to Tukey's HSD multiple comparison test (with the RMSE), many are not statistically significant. In fact, none of the improvements in groups of variables relative to the immediately adjacent group were statistically significant (Figure S2).

3.2.2. Model Prediction

Five forest variables were predicted from Sentinel-2-derived predictors and other ancillary variables. We considered two density variables (number of stems per hectare and basal area), one size-related variable (dominant height) and two yield variables (total over bark volume and total aboveground biomass). The models that produced the worst results were the number of stems per hectare (N), with R^2 ranging from 0.18 to 0.26 (relative RMSE ranged from 51.8% to 67.0%), followed by dominant height (H_0), with R^2 ranging from 0.33 to 0.37 (relative RMSE ranged from 22.3% to 30.5%). Yield variables, total over bark volume (TV) and aboveground biomass (AGB) and basal area (G) produced the best-fitting results, with R^2 greater than 0.40 (except G , for *P. radiata*, with $R^2 = 0.39$) and reaching up to 0.46 (Table 9) (RMSE% ranged from 44.6% to 61.9%). However, all models displayed very low bias, with higher values for N models (values of Bias% ranged between -0.024% and 0.001%) (Table 9; Figure S1). Therefore, the models can be considered unbiased as the Bias% was always lower than 1% (average value of -0.006%).

Figure 4 shows the typical overall RMSE% increase for the validation dataset and the reduction in the Bias% as a consequence of the 100 iterations. These graphs show the model performance for classes of the predicted variable; all models (regardless of the response variable) performed similarly, overestimating lower values and underestimating higher values, although to a much lesser extent.

Table 9. Summary of the contribution of each group of independent variables to the predictive ability of models and their goodness-of-fit statistics. All values represent the mean of 100 model runs (i.e., 10 replicates, each with 10-fold cross-validation). The numbers in brackets represent the number of variables included in the model, and the number outside brackets indicate the accumulated importance measure expressed in relative values (VIM_R), where Avg. = average, VIM_R value of the five models, R^2 = pseudocoeficient of determination, Bias = bias, Bias% = relative bias, RMSE = root mean square error, RMSE% = relative root mean square error of the best models.

		<i>Eucalyptus globulus</i>						<i>Pinus pinaster</i>						<i>Pinus radiata</i>						
		<i>N</i>	<i>G</i>	<i>H₀</i>	<i>TV</i>	<i>AGB</i>	<i>Avg.</i>	<i>N</i>	<i>G</i>	<i>H₀</i>	<i>TV</i>	<i>AGB</i>	<i>Avg.</i>	<i>N</i>	<i>G</i>	<i>H₀</i>	<i>TV</i>	<i>AGB</i>	<i>Avg.</i>	
Independent variables	Group	(1)	0.24 (2)	0.47 (4)	0.18 (2)	0.26 (2)	0.48 (6)	0.33	0.29 (2)	0.53 (3)	0.25 (3)	0.51 (4)	0.43 (3)	0.40	0.41 (5)	0.35 (4)	0.32 (4)	0.44 (4)	0.39 (3)	0.38
		(2)	0.55 (6)	0.36 (5)	0.47 (9)	0.56 (6)	0.52 (4)	0.50	0.34 (5)	0.20 (2)	0.23 (5)	0.13 (2)	0.23 (3)	0.23	0.28 (3)	0.31 (3)	0.29 (4)	0.24 (3)	0.22 (3)	0.26
		(3)	0.07 (1)	0.11 (2)	0.07 (2)	0.06 (1)	-	0.06	0.09 (3)	0.27 (3)	0.15 (3)	0.14 (2)	0.16 (2)	0.16	0.14 (1)	0.16 (3)	0.16 (3)	0.10 (2)	0.13 (4)	0.13
		(4)	0.14 (2)	0.06 (1)	0.17 (4)	0.13 (2)	-	0.10	0.20 (3)	-	0.23 (3)	0.07 (1)	0.08 (1)	0.12	0.17 (2)	0.17 (3)	0.23 (4)	0.22 (4)	0.27 (5)	0.21
		(5)	-	-	0.11 (3)	-	-	0.02	0.08 (1)	-	0.15 (2)	0.16 (2)	0.10 (1)	0.10	-	-	-	-	-	0.00
No. of variables		11	12	20	11	10		14	8	16	11	10		11	13	15	13	15		
Goodness-of-fit statistics	R^2		0.26	0.46	0.33	0.46	0.43		0.23	0.46	0.37	0.45	0.41		0.18	0.39	0.37	0.44	0.42	
	Bias		-5.44	-0.07	-0.02	-0.84	-0.92		-13.65	-0.10	-0.05	-1.02	-0.66		-6.85	-0.02	0.03	0.08	0.08	
	Bias%		-0.007	-0.004	-0.001	-0.006	-0.009		-0.024	-0.005	-0.003	-0.006	-0.007		-0.015	-0.001	0.001	0.000	0.001	
	RMSE		432.63	9.06	6.01	87.43	61.57		384.72	10.01	5.08	89.7	52.79		268.7	10.61	5.03	111.73	58.03	
	RMSE%		51.8	49.5	28.0	58.9	61.9		67.0%	44.6	30.5	54.7	57.2		59.2	38.1	22.3	45.4	45.5	

According to the VIM_R scores shown in Table 9, spectral bands contributed most to the *P. pinaster* and *P. radiata* models (averaged accumulated VIM_R of 40% and 38%, respectively), followed by the spectral indices (averaged accumulated VIM_R of 23% and 26%, respectively), with texture and terrain variables contributing 16% and 12% in *P. pinaster* and 13% and 22% in *P. radiata*. Climatic variables contributed the remaining 10% in *P. pinaster* and 0% in *P. radiata* (Table 9). However, important differences were observed according to the spectral variables with the highest VIM_R score; thus, the spectral bands that contributed most to the *P. pinaster* models were the short-wave infrared bands *B11* and *B12*, representing 71% of the total contribution of this group of variables to the set of models, followed by red band (*B4*) and Red-Edge-1 (*B5*). By contrast, the green band (*B3*) and red band (*B4*) contributed most to the set of models in *P. radiata*, representing 43% of the contribution of this group of variables, followed by near-Infrared (*B8*) and short-wave infrared *B11* (Table 10). The spectral indices that contributed most to *P. radiata* models were *EVI*, *GNDVI*, *TCB* and *ARI*, with an accumulated VIM_R of 0.95, which represented 73% of the contribution of this group of variables. For *P. pinaster*, the corresponding indices were *MARI*, *GNDVI*, *EVI* and *NBR2*, with an accumulated VIM_R of 0.79 which represents 70% of the contribution of this group of variables. The *NDVI* texture indices that contribute most to the models were *CON*, *DIS*, *ENE* and *COR* for *P. radiata* and *MEN*, *SDT*, *ENT* and *DIS* for *P. pinaster*, with accumulated VIM_R of 0.52 and 0.74, which represent contributions of 78% and 91%, respectively. The terrain variables that contributed most to the forest models were *WI*, *SLP*, *ASP* and *ELV* for *P. radiata* and *ELV*, *WI*, *PLC* and *SLP* for *P. pinaster*, with accumulated VIM_R of 0.87 and 0.58, which represent contributions of 81% and 100%, respectively. Climatic variables did not contribute to the *P. radiata* models, but did contribute to the *P. pinaster* models. Thus, only *MAT* contributed, with an accumulated VIM_R of 0.31, which represents a contribution of 63%.

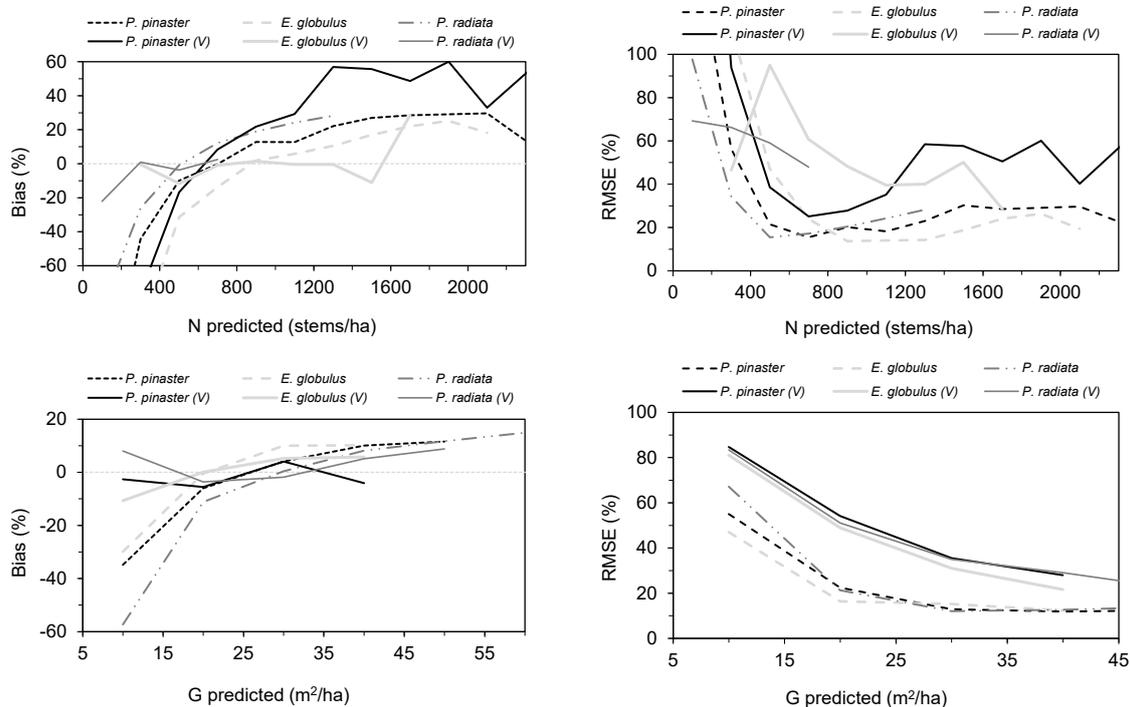


Figure 4. Cont.

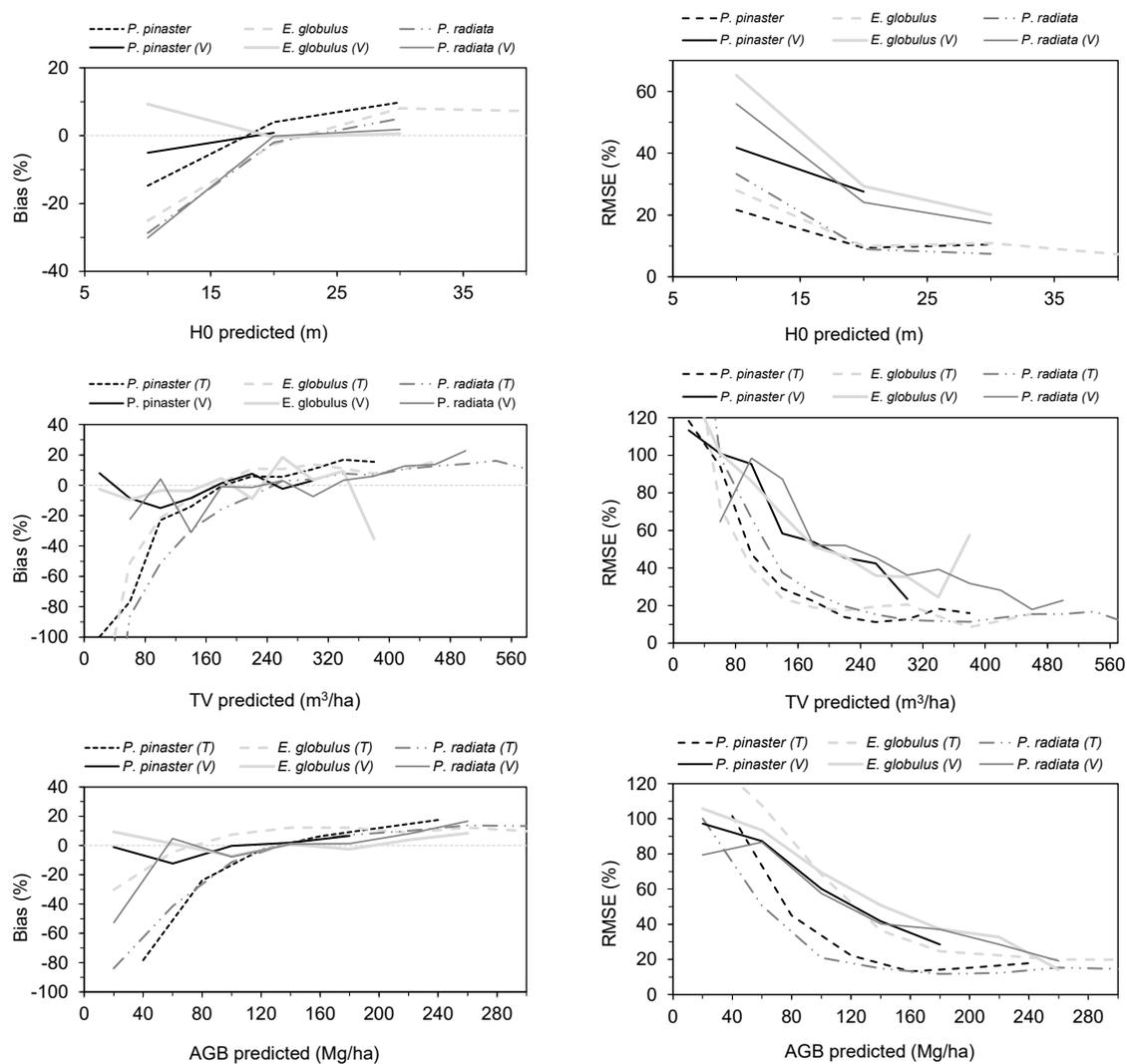


Figure 4. Plots of the distribution of relative bias and root mean square error (RMSE) of models by classes of the predicted variable in training (T) and the 100 model runs (10-repeated, 10-fold cross-validation) (V), where N = number of stems per hectare, G = basal area, H_0 = dominant height, TV = total over bark volume and AGB = aboveground biomass.

For *E. globulus*, spectral indices contributed most to the forest models (averaged accumulated $VIM_R = 0.50$), with ARI , TCW , EVI and TCB contributing with an accumulated VIM_R of 1.38, which represented 55% of the total importance of this group of variables (Table 9). The following most important group of variables was the spectral bands (averaged accumulated $VIM_R = 0.33$). The four most relevant were $B11$, $B6$, $B5$ and $B7$, which contributed an accumulated VIM_R of 1.48, representing 90% of the importance of this group of variables. Terrain variables (averaged accumulated $VIM_R = 0.10$) were the third most important group of variables according to the averaged accumulated VIM_R score, with ASP , HLL , PLC and ELV representing 55.49% of the total importance of this group of variables. Texture was fourth group according to its contribution to ability prediction of eucalypt forest models, with an averaged accumulated $VIM_R = 0.06$. The variables MEN , HOM , COR and SDT contributed with an accumulated VIM_R of 0.41 (100% of the total importance of this group). Finally, climate made a very small contribution, with an averaged accumulated $VIM_R = 0.02$.

Table 10. Variables included in the models and their relative variable importance values (VIM_R). Sum = sum of the VIM_R values of the five models.

Type	Indep. Variable	<i>Eucalyptus globulus</i>						<i>Pinus pinaster</i>						<i>Pinus radiata</i>					
		N	G	H ₀	TV	AGB	Sum.	N	G	H ₀	TV	AGB	Sum.	N	G	H ₀	TV	AGB	Sum.
Spectral bands	B2	-	-	-	-	0.06	0.06	-	-	-	-	-	-	0.09	0.06	-	-	-	0.15
	B3	-	-	-	-	-	-	-	-	-	-	-	-	0.07	0.09	-	0.10	0.16	0.42
	B4	-	-	-	-	-	-	-	0.11	0.08	-	0.19	0.07	0.08	0.06	0.10	0.09	-	0.40
	B5	0.11	-	0.08	-	0.10	0.29	-	0.08	0.09	-	0.17	-	-	0.12	-	-	-	0.12
	B6	0.13	0.11	-	-	0.06	0.30	-	0.07	-	0.04	0.11	-	-	0.08	-	-	-	0.08
	B7	-	0.05	-	0.06	0.04	0.15	-	-	-	-	-	-	-	-	-	-	-	-
	B8	-	-	-	-	-	-	-	0.07	-	-	-	0.07	-	0.12	-	0.10	0.14	0.36
	B8A	-	0.06	-	-	0.04	0.10	-	-	-	0.04	0.04	-	-	0.06	-	-	-	0.06
	B11	-	0.26	0.10	0.20	0.19	0.75	0.20	0.39	0.06	0.19	0.34	1.18	0.11	-	-	0.14	-	0.25
	B12	-	-	-	-	-	-	0.08	-	-	0.14	-	0.22	0.07	-	-	-	-	0.07
Spectral indices	ARI	0.10	0.10	0.06	0.11	0.08	0.45	-	-	-	-	-	0.15	-	-	-	-	-	0.15
	CRE	-	-	-	-	-	-	-	-	-	-	-	0.06	-	-	-	-	-	0.06
	EVI	-	0.08	0.05	0.09	0.08	0.30	0.06	0.10	-	-	-	0.16	-	0.08	0.10	0.11	0.13	0.42
	EVI2	-	-	-	-	0.04	0.04	-	-	-	-	-	-	-	-	-	-	-	-
	GNDVI	-	0.06	-	-	-	0.06	0.08	-	0.04	0.06	-	0.18	-	0.06	0.05	0.05	0.05	0.21
	MARI	-	-	-	-	0.05	0.05	-	0.10	0.04	0.07	0.10	0.31	-	-	-	-	-	-
	MCARI	-	-	0.05	0.07	0.06	0.18	-	-	-	-	-	-	-	-	-	-	-	-
	MSAVI	-	0.07	-	0.06	-	0.13	-	-	-	-	0.05	0.05	-	-	-	-	0.04	0.04
	MSI	0.08	-	-	-	-	0.08	0.05	-	-	-	-	0.05	-	-	0.04	-	-	0.04
	NBR	-	-	-	-	-	0.07	-	-	0.05	-	-	0.05	-	-	-	-	-	-
	NBR2	-	-	0.03	-	-	0.03	0.10	-	0.04	-	-	0.14	0.06	-	-	-	-	0.06
	NDMI	-	-	0.08	-	-	0.08	0.05	-	0.06	-	-	0.11	-	-	-	-	-	-
	NDVI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	PSSR	0.08	-	0.03	-	-	0.11	-	-	-	-	-	-	-	-	-	-	-	-
	SAVI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TCA	0.07	0.06	0.04	-	-	0.17	-	-	-	-	-	-	-	-	-	-	-	-	
TCB	0.14	-	0.07	-	-	0.21	-	-	-	-	-	-	-	-	-	-	-	-	
TCG	-	-	0.06	0.06	0.05	0.17	-	-	-	-	0.08	0.08	-	0.17	-	-	-	0.17	
TCW	-	-	0.09	0.17	0.16	0.42	-	-	-	-	-	-	-	-	0.09	-	-	0.09	
Texture	SEC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	0.03
	CON	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.04	0.09
	COR	-	0.05	-	-	-	0.05	-	-	-	-	-	-	0.14	0.06	-	-	-	0.20
	DIS	-	-	-	-	-	-	0.03	0.08	-	-	-	0.11	-	-	0.05	0.06	0.03	0.14
	ENE	-	-	-	-	-	-	0.03	-	-	-	-	0.03	-	0.05	-	0.04	-	0.09
	ENT	-	-	-	-	-	-	0.03	-	0.04	-	-	0.07	-	-	-	-	-	-
	HOM	0.07	-	-	-	-	0.07	-	-	0.04	-	-	0.04	-	0.05	-	-	0.02	0.07
	MAX	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MEN	-	0.06	0.04	0.06	-	0.16	-	0.10	0.06	0.07	0.09	0.32	-	-	-	-	-	-
SDT	-	-	0.04	-	-	0.04	-	0.09	-	0.07	0.08	0.24	-	-	0.05	-	-	0.05	
Terrain	ASP	-	0.06	0.04	0.06	-	0.16	-	-	-	-	-	-	0.07	0.05	0.06	0.06	0.24	
	ASR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	CU	-	-	-	-	-	-	-	-	-	-	-	-	-	0.06	-	-	0.06	
	ELV	-	-	0.04	-	-	0.04	-	0.14	0.07	-	0.21	-	-	-	0.05	0.06	0.11	
	HLI	0.07	-	-	0.07	-	0.14	-	-	-	-	-	-	-	-	-	-	-	
	PLC	0.07	-	-	-	-	0.07	0.06	-	-	-	0.08	0.14	-	0.05	-	-	0.05	
	PFC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	
	SLP	-	-	0.04	-	-	0.04	0.06	-	0.04	-	-	0.10	0.08	-	0.07	0.05	0.05	
	TSI	-	-	0.04	-	-	0.04	-	-	-	-	-	-	-	0.05	-	-	-	
	WI	-	-	-	-	-	-	0.08	-	0.05	-	-	0.13	0.09	0.06	-	0.06	0.06	0.27
Climatic	TM	-	-	0.04	-	-	0.04	-	-	-	0.09	-	0.09	-	-	-	-	-	
	TMAX	-	-	0.04	-	-	0.04	0.08	-	0.06	0.07	0.10	0.31	-	-	-	-	-	
	TMIN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	PT	-	-	0.03	-	-	0.03	-	-	0.09	-	-	0.09	-	-	-	-	-	
	RA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

3.3. Results of Mapping Forest Variables

Spatially continuous maps of the forest variables resulting from application of the best models for the three major commercial timber plantations (*E. globulus*, *P. pinaster* and *P. radiata*), occupying areas greater or equal to 80% (according to the Spanish Forest Map) were generated. Figure 5 shows, as an example, the distribution of TV (m³ ha⁻¹) for the different forest species across the study area. Finally, average values per hectare and total Sentinel-2-based wall-to-wall predictions for the five forest variables and for the three species were generated per region (Table 11).

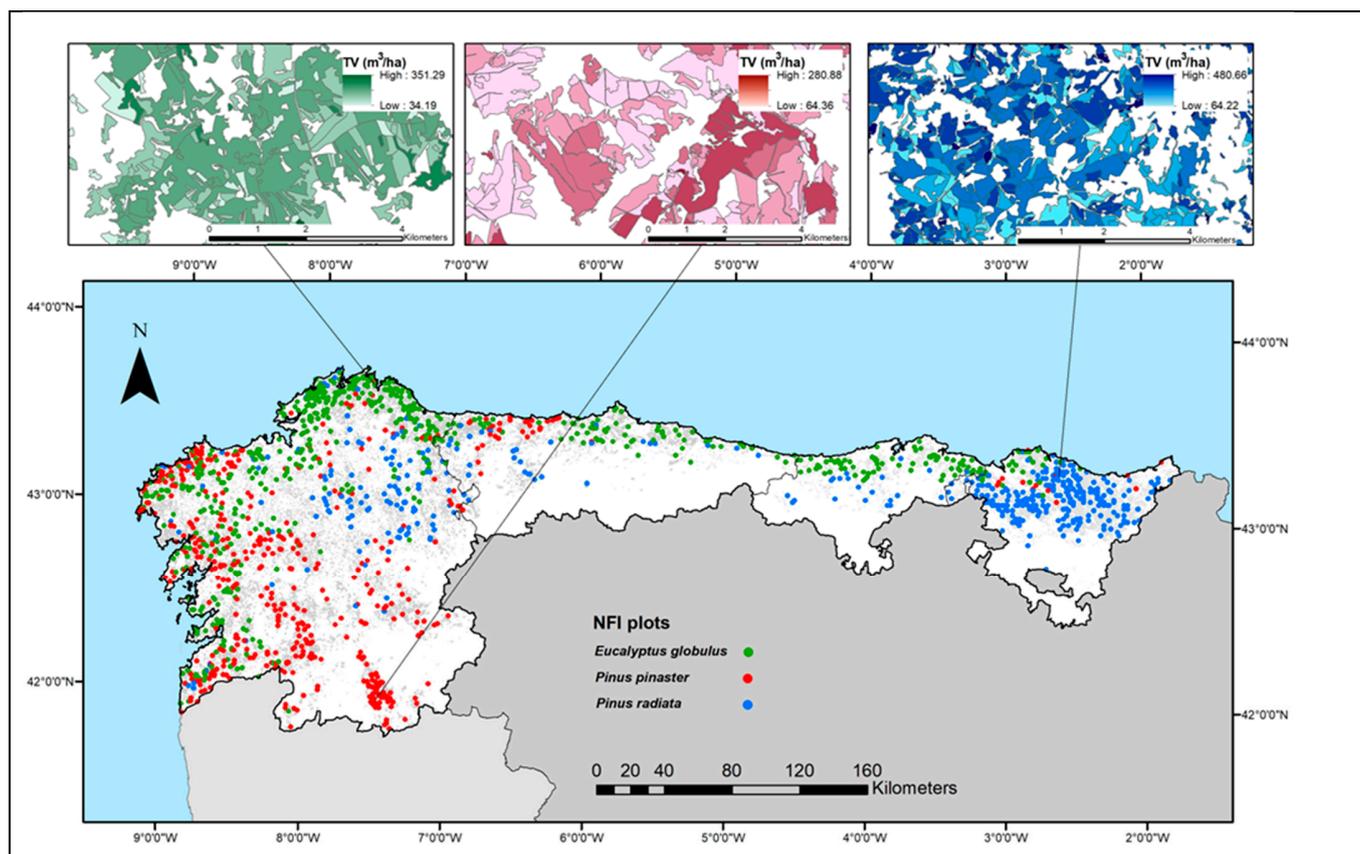


Figure 5. Example of the spatial distribution of the total over bark volume, TV ($m^3 ha^{-1}$) in the four regions in northern Spain under study (bottom). Top: Detailed map (10×10 m/pixel of spatial resolution) for this variable.

Table 11. Table showing the average and standard deviation values per hectare and total of the Sentinel-2-based wall-to-wall predictions for the three forest species and the four regions in northern Spain.

		Region							
		Galicia		Asturias		Cantabria		Basque Country	
		Avg. (Sd)	Total	Avg. (Sd)	Total	Avg. (Sd)	Total	Avg. (Sd)	Total
<i>E. globulus</i>	N	816.42 (120.11)	108,162,865.38	782.00 (131.34)	30,174,276.15	790.58 (129.26)	26,771,979.95	868.86 (180.21)	8,625,895.65
	G	18.21 (3.95)	2,412,527.76	15.79 (3.34)	609,186.45	16.89 (4.07)	572,048.59	20.12 (6.37)	199,773.22
	H_0	21.66 (2.03)	2,870,200.23	20.17 (1.49)	778,171.45	21.25 (1.88)	719,627.29	22.23 (2.81)	220,672.33
	TV	152.15 (38.17)	20,157,482.01	126.57 (29.66)	4,883,988.79	141.38 (38.21)	4,787,726.89	170.94 (61.01)	1,697,084.24
	AGB	103.48 (26.00)	13,709,146.49	86.45 (19.72)	3,335,870.38	95.80 (25.94)	3,244,040.50	117.41 (41.94)	1,165,589.52
<i>P. pinaster</i>	N	663.05 (129.72)	111,420.57	605.84 (92.03)	8,788,913.94	809.37 (271.92)	173,420.57	794.72 (185.78)	4,177,647.49
	G	21.19 (4.86)	3,569,806.40	22.90 (4.05)	322,160.32	25.96 (9.04)	5,561.59	27.65 (5.65)	145,354.34
	H_0	15.88 (2.54)	2,675,987.48	15.95 (1.62)	231,398.86	16.19 (2.66)	3,468.13	17.69 (1.57)	92,982.27
	TV	156.43 (41.86)	26,353,790.70	164.17 (32.25)	2,381,631.85	197.49 (78.15)	42,316.14	208.83 (43.58)	1,097,773.53
	AGB	87.27 (24.04)	14,701,927.30	113.07 (26.48)	1,640,230.48	66.97 (16.88)	14,349.93	103.61 (26.08)	544,669.58
<i>P. radiata</i>	N	513.70 (87.71)	30,609,531.69	521.11 (76.32)	9,831,803.62	466.87 (76.92)	3,032,877.78	476.96 (64.09)	54,692,959.82
	G	26.05 (4.10)	1,552,099.38	26.99 (4.23)	509,313.68	26.32 (4.93)	171,007.17	27.80 (5.46)	3,187,960.25
	H_0	20.52 (1.47)	1,222,504.17	20.44 (1.83)	385,672.55	21.70 (2.17)	140,998.67	23.24 (2.18)	2,664,458.16
	TV	215.59 (38.68)	12,846,469.77	222.08 (41.58)	4,189,903.77	230.08 (50.87)	1,494,652.27	259.30 (61.23)	29,733,439.08
	AGB	114.94 (20.58)	6,848,897.27	116.21 (21.72)	2,192,591.69	114.32 (27.88)	742,616.38	132.73 (30.24)	15,219,668.09

where Avg. = mean value of the forest variable (units of the variable per hectare); Sd = standard deviation of variables; Total = total amount of the variable (units of the variable); N = number of stems, G = basal area (m^2), H_0 = dominant height (m), TV = total over bark volume (m^3) and AGB = aboveground biomass (Mg).

4. Discussion

4.1. Impacts of Geolocation Accuracy, Image Correction Level and Fitting Algorithm on Total Volume Estimation

The study findings did not show any clear impact of the plot geolocation accuracy on the stand volumes estimated using Sentinel-2 data. Thus, contrary to what might be expected, the result of using all plots was better than the result of using only sub-meter plot accuracy. This seems to suggest that the model performance mainly depends on other characteristics of the plots used for the model development (e.g., stand age, density, ...) rather than on the precision of the geolocation.

While it is true that accurate geographical co-registration of remote sensing data and field plots has been recognized as necessary [24,68], its impact strongly depends on the size of the field plot and on the type of the remote sensor used (active or passive) and its spatial resolution.

Thus, ref. [24] showed that larger plot sizes (300–400 m²) compensate for errors; these results were later confirmed and extended by [69], who found that prediction improved markedly as plot size increased from 314 m² (10 m radius) to 1964 m² (25 m radius), the maximum size of the SNFI plots. In our study, 83.33% of the plots were of radius equal or greater than 15 m (52.08% have a radius of 25 m). There are two main reasons underlying these results [69]: (i) large plots capture more on-ground variability and therefore are more resistant to the harmful effects of co-registration errors and (ii) large plots maintain a greater amount of spatial overlap between land plot and LiDAR data. This latter was demonstrated by [35], who showed that for plot size of 1964 m² (25 m radius) and positioning errors of 5 and 10 m (much larger than the 3–5 m theoretical errors), the areas overlapping a plot in a correct position and a plot located in an altered position were 84.3% and 74.7%, respectively. These previous arguments, which mainly concern LiDAR actively remotely sensed data, are also applicable to passively remotely sensed data. Ref. [70] found that co-registration errors have a greater impact on stand volume estimates derived from LiDAR data than on those derived from Landsat data, suggesting that geolocation precision requirements are currently lower when using optical data from satellites. Moreover, this requirement will be less demanding even when the spatial resolution of the sensor is lower (i.e., 20 m/pixel vs. 10 m/pixel), which is consistent with the plot size arguments expressed above. This is likely because the spatial resolution of the images (i.e., 20 m/pixel) implies that the same radiometric value corresponds to an area of 400 m² (20 × 20 m pixel size). Our findings therefore suggest that expected positioning errors of between 5 and 10 m of SNFI plots do not have a significant influence on the accuracy of estimation of forest variables from Sentinel-2 images.

The best-fitting algorithm and the image correction levels were selected together, as they are mutually dependent. MARS yielded better results for L1C and L2A-AC correction levels, whereas RF performed best with the L2A-ATC and also yielded the best values of the goodness-of-fit statistics; the fitting algorithm and the image correction level selected to develop the final models were, respectively, RF and L2A-ATC. This finding is consistent with those of previous studies demonstrating the superior performance of the RF algorithm over the MARS approach and Sentinel-2 data [71].

When dealing with forest on steep terrain and north or northwest orientations (higher levels of shade in the northern hemisphere), better results are expected a priori for forest variable estimation when topographic correction of the images is carried out. This is because topographic correction can reduce the effects of varying topography/terrain surfaces and associated shading on spectral reflectance. This correction is more effective when an accurate terrain digital model is used, as it will determine the accuracy of the aspect and slope determinations on which the correction accuracy strongly depends [72]. Although the mean aspect is similar for plots of three species (ca. 179°), greater improvement in the model performance was observed, as the slope increased, when topographic correction was implemented.

4.2. Model Accuracy and Role of Different Groups of Predictor Variables

The models based on number of stems per hectare (N) and dominant height (H_0) were the least precise (average R^2 of 0.22 and 0.36, respectively). By contrast, models of density (G) and yield variables (TV and AGB) produced the best results, with R^2 of 0.43 and 0.44, respectively. This is not surprising, as remote optical sensors are predicting yield (volume or biomass) or density variables (site occupancy) better than predicting the number of stems per hectare or stand height (e.g., [49,73,74]). In fact, these sensors are considered unsuitable for predicting vertical vegetation structures such as stand height [48], which is accurately predicted with LiDAR data. However, the sensors perform well with yield or site occupancy variables, as the data provided are strongly correlated with tree canopy size, which determines the canopy reflectance [75]. Thus, although the number of stems per hectare is often included as a density variable, it is only valid at the initial forest stand stage, where all stems are of the same size. At later stages, the number of stems per hectare is not a suitable measure of density, as site occupancy variables must be a function of at least of the number of stems and an average tree size measure [76].

All models performed similarly, with overestimation of lower values and underestimation of high values of the predicted variables. This is a typical result when predicting forest variables with optical data (e.g., [59,73,77]). It may occur because in low-stocked forest (low values of density or yield), the canopy reflectance tends to include a greater contribution from shadows, soil background and understory and a lower contribution from green leaves. The opposite will be true for well-stocked forest. Moreover, many authors have observed that canopy data obtained by optical and radar sensors tend to be saturated in excessively dense forests (approximately at $250 \text{ m}^3 \text{ ha}^{-1}$ or 150 Mg ha^{-1}), which greatly reduces the accuracy of estimation (e.g., [48,59,78]), although this phenomenon was generally not observed in our cross-validation results from 100 runs, for two possible reasons: (i) the lack or scarcity of mature forest stands and (ii) the use of indexes related to red-edge and texture variables as predictors. Some authors have reported that red-edge indexes (e.g., [79,80]) and texture variables [81] can overcome the saturation problem and increase the accuracy of estimation of forest yield variables, suggesting that inclusion of these variables may contribute to increasing the upper limit of saturation reported in the bibliography.

Considering the weights of the spectral bands (assessed as the VIM_R of each band) in relation to the predictive ability of models, the species seem to be separated into two distinct groups; one formed by *E. globulus* and *P. pinaster* and the other by *P. radiata*. Regarding the first group there is a negligible contribution of the visible $B2$, $B3$ and $B4$ bands in *E. globulus* and a moderate contribution in *P. pinaster*, and the short-wave infrared (SWIR) band ($B11$) is the spectral band that most contributes the explanatory ability of density (G) and yield models (TV and AGB). The variable $B11$ accounted for 38% to 81% of the importance score of the contribution of the spectral band. Many authors have previously pointed out that SWIR spectral bands are more closely related to vegetation properties such as water content, canopy biomass and density or yield variables (e.g., [75,82,83]).

The four most important spectral bands are $B11$, $B6$, $B5$ and $B7$, contributing with an accumulated VIM_R of 1.48, which represent 90.08% of the importance of this group of variables for *E. globulus*. Thus, the red-edge bands ($B5$, $B6$ and $B7$) together contribute most, after $B11$, to the *E. globulus* model. For *P. pinaster*, the red-edge bands $B5$ and $B6$ and the visible $B4$ red band are the most important after the $B11$ and $B12$ SWIR bands. The predictive power of red-edge bands has been reported in recent studies involving tree species classification [60], forest biophysical variables (e.g., [20,41]) and average tree size and forest yield variable estimations [73].

However, for *P. radiata*, the greatest contributions were made by the green band ($B3$) and near-infrared band ($B8$), similarly to the findings obtained by [84] in the Western Carpathian Mountains with Norway spruce stands (both with dark green canopies). Globally, the behavior of *P. radiata* spectral bands was different to that observed for *P. pinaster* and *E. globulus*, with the greatest contribution by green ($B3$), red ($B4$) and infrared ($B8$) bands. This ranking of the spectral bands response may be because *E. globulus* and *P. pinaster*

stands have light green, relatively low-density canopies which visually contrast with the denser and dark green radiata pine canopies.

Spectral indices contribute twice as much to *E. globulus* models than to *P. pinaster* and *P. radiata* models, so that the spectral response (spectral indices + spectral bands) is much stronger in eucalypt than pines. The Anthocyanin and Modified Anthocyanin Reflectance indexes (*ARI* and *MARI*) are the spectral indexes that contribute most to improving forest model estimates in *E. globulus* and *P. pinaster*, respectively. These indexes are related to the anthocyanin content present in leaves and their values increase as leaves change due to tree growth or death of the leaves [85]. This is not surprising as the indices incorporate some red-edge bands *B5* (*ARI*) and *B5* and *B7* (*MARI*) in addition to the visible green band *B3*. Both indices are positively correlated with yield variables ($r = 0.35$ for *ARI* in *E. globulus* and $r = 0.12$ for *MARI* in *P. pinaster*). The Enhanced Vegetation Index (*EVI*) index was the most important spectral index in *P. radiata* and the third most important in the remaining species. This index was developed to optimize the vegetation signal, correcting reflected light distortions caused by particulate matter suspended in the air, as well as by influence of background data under the vegetation canopy [86,87]. According to [88], *GNDVI* displays greater sensitivity to changes in chlorophyll content than *NDVI*, which is strongly associated with nitrogen. These authors further asserted that *GNDVI* exhibits a sensitivity to chlorophyll-a concentration that is at least five times higher than that of *NDVI*, making it particularly advantageous for distinguishing stressed and senescent vegetation. In the present study, the *GNDVI* was ranked as the second most significant spectral index for *P. pinaster* and *P. radiata*, which may be due to its greater significance in the bands of the visible and near-infrared regions of the electromagnetic spectrum. This finding is consistent with the results obtained by [89] in the Lousã Region of Portugal, where *P. pinaster* constitutes the predominant vegetation cover. The Tasseled Cap Wetness (*TCW*) index was the second most important for eucalyptus. This index is sensitive to vegetation moisture content into the pixel, and is valuable for differentiating deforestation and degradation [90]. Thus, considering that moderate and even severe defoliation by *Gonipterus platensis* is frequent in many stands in the study area, this index may be amplifying the effect of not capturing individual bands in isolation. Moreover, in our study, we found that the *TCW* index was negatively correlated with total over bark volume ($r = 0.48$), as also observed by [91], and with aboveground biomass ($r = 0.46$), which may indicate that the vegetation has a lower moisture content in well-stocked stands (which are less dense).

The results of adding texture variables to spectral bands and spectral indices improved R^2 by on average 2.87% in *E. globulus* models, and by 8.60% and 12.90% in *P. pinaster* and *P. radiata* models; the final models showed that texture variables are between 2.1 and 2.5 times more important in *P. pinaster* and *P. radiata* than in *E. globulus*. The overall importance of the texture measures on the predictive capacity of the models is consistent with the findings reported by [43], as the spectral responses (spectral bands and spectral indices) play a more important role in forest variable estimation than textural images when the forest stand structure is relatively simple (e.g., eucalypt plantations), although textural images become more important as the complexity of the forest structure increases (e.g., maritime pine and radiata pine stands). This is because texture measures increase the spatial information about the stand and therefore better capture their structural characteristics [92]. Many authors have increased the accuracy of forest models by adding texture measures to the spectral bands and indexes (e.g., [93–95]).

Terrain and climatic features affect the environmental conditions for growth and may be important for predicting forest variables. Overall, these variables were more important in *P. pinaster* and *P. radiata* stands, in which spectral responses have been found to be less important than in *E. globulus* stands. Elevation (*ELV*) is the most important terrain variable in *P. pinaster* and is negatively correlated with both H_0 and *TV*, which is consistent with the fact the stands with the highest productivity of this species in North Spain occur in areas close to the coast [96]. This variable may even be the most important explanatory variable in areas characterized by strong elevational gradients [84]. The topographic wetness index

(WI) is usually positive correlated with yield variables in arid areas [97]. However, the inclusion of this variable in *P. radiata* lead to a negative correlation with yield predictions, which seems to indicate that in rainy climates like in north-western Spain (annual rainfall of between 1000 and 1300 mm), high levels of biomass for this species coincide with zones with moderate or low levels of soil moisture. According to [87], prediction of eucalyptus stand attributes was significantly influenced by various terrain attributes, including heat load index, relative slope position, total curvature, aspect and terrain roughness index. These terrain attributes were responsible for 54.5%, 41.6%, and 53.8% of the selected variables used by RF models to predict volume, basal area and DBH, respectively.

The inclusion of climate variables was only important for *P. pinaster*, as the yield models included the maximum (*TMAX*) and average temperature per month (*TM*); both of which are positively correlated with yield variables. This is consistent with the species autoecology as *P. pinaster* is the most widely distributed of the species considered, in accordance with the climate conditions, and its distribution and productivity in north Spain are also positively correlated with these variables [96].

Previous yield models, predicting *TV* and *AGB*, were built for the same species and for much of the same region in North Spain by using public nationwide Airborne Laser Scanner (ALS) data with 0.5 pulses/m². The models yielded results with an RMSE% ranging from 30.8 to 38.3% and 31.7 to 38.3%, respectively [14], whereas, in this study, the errors ranged from 45.4% to 58.9% and 45.5% to 61.9%, respectively. However, Sentinel-2-based estimates, although less precise than those obtained with ALS data, are unbiased and therefore we expect accurate estimates for an area of one hectare, as the values are obtained by averaging the values obtained in 100 pixels with an expected error compensation.

4.3. Limitations and Future Developments

When designing a network of field plots to be used together with remotely sensed data, spatial correlation of the plots and pixels centers (co-registration) should be a prerequisite to eliminate any possible sources of imprecision and bias of model estimates. As field plots, we used the SNFI systematic grid that was first established in 1986 [98] independently of any remote sensing source of data to that date. In the present study, the discrepancy between pixel size of the Sentinel-2 images (400 m²) and the SNFI field plots size (314 to 1964 m²) and their respective centers could also lead to some inconsistencies in the results.

Although the plots were chosen on the basis of various forest conditions to ensure maximum representativeness (different plantation schedules or/and thinning treatments and common pest and disease conditions), the sample size may be considered somewhat restricted. To address this point, we used the k-fold cross-validation method, as proposed by [99], to mitigate overfitting and minimize the risk of uncertainty in the predictions [100]. In general, our research prioritized the significance of the samples in capturing biomass variability throughout the study region. Further research will aim for true validation of the models from real data on timber harvesting to confirm the results obtained in the cross-validation procedure.

Moreover, the estimation accuracy is greatly reduced in excessively dense forests due to the saturation of canopy information obtained by optical data [48]. Furthermore, saturation of forest *AGB* data is affected by topographic features in the study area, which can alter the distribution and composition of tree species, vegetation growth rates, and spectral reflectance. Specifically, factors such as elevation, slope and aspect play a crucial role in this regard [78].

The developed models are intended for application to pure stands (basal area of the target species greater or equal than 80%), and development of a model for mixed stands in which at least 50% or more of the stand basal area corresponds to one or more of the three forest species studied remains a task for the future.

Finally, one of the most important applications of our models is current assessment of the timber resources at regional level. This application requires up-to-date, accurate mapping of the forest species coverage. However, at present, the model predictions

(spatially continuous maps) must be clipped with the area occupied by the species according to the Spanish Forest Map, which is updated every 10 years. The combined use of the model predictions developed here, and land cover classification models also based on Sentinel-2 images will enable automatic estimation of timber resources. We are already developing land cover maps that will provide annually updated estimates of forest timber resources and overcome the drawbacks of the current method.

5. Conclusions

This research has shown that it is possible to use Spanish National Forest Inventory (SNFI) field data and Sentinel-2 (spectral bands, spectral indices and texture variables) and ancillary data (terrain and climatic variables) to develop high-resolution forest models to estimate stand variables with reasonable accuracy (number of stems per hectare, basal area, dominant height, total stand volume and aboveground biomass) for major commercial timber plantations in northern Spain.

The findings of this study revealed the importance of carrying out topographical corrections of the images in steeply sloping terrain or areas with complex topography. In contrast to findings regarding airborne or satellite LiDAR data, we found that SFNI plots can be used to develop accurate forest models from optically sensed data without the need for sub-meter geolocation. The gain in model accuracy as a consequence of sequentially including predictor variables (spectral bands, spectral indices, texture variables, terrain, and climatic variables) depended on a complex mixture of stand variables and forest species (and their forest structure and distribution), and therefore we always recommend using this approach to develop such models. We highlight the importance of the availability of public databases as the National Forest Inventories field plots and publicly available remotely sensed data provided by space agencies, which enable development of accurate forest resources prediction models at regional or national scales when used together.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/f15010099/s1>, Table S1. Texture variables formulation employed in the study. Table S2. Terrain variables formulation employed in the study. Figure S1. Scatter plots of the observed vs. predicted values after 10 repeated 10-fold cross-validation (100 model runs). The dashed red line represents the linear model fitted to the scatter plot, and the solid black line represents the line of slope equal to 1. N = number of stems per hectare, G = basal area, H_0 = dominant height, TV = Total over bark volume, AGB = Total aboveground biomass. Figure S2. Results of the Tukey HSD multiple comparisons test for RMSE of the five forest predictor variables for the three different species (*Pinus pinaster*, left column; *Pinus radiata*, centre column; and *Eucalyptus globulus*, right column) and the five groups of independent variables considered. The same letter indicates that the values are not significantly different. Different letters indicate that the values are significantly different ($p \leq 0.05$). (1) = Spectral bands; (2) = Spectral bands + spectral dices; (3) = Spectral bands + spectral indices + texture variables; (4) = Spectral bands + spectral indices + texture variables + terrain variables; (5) = Spectral bands + spectral indices + texture variables + terrain variables + climatic variables; N = Number of stems per hectare; G = Basal Area; H_0 = Dominant height; TV = Total over bark volume; AGB = Total aboveground biomass. The box-plot inserted in a red-dashed line rectangle correspond to the data group selected as the best option for each species.

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