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# Updating national forest inventory estimates of growing stock volume using hybrid inference

Sonia Condés [a,*], Ronald E. McRoberts [b]

[a] Department of Natural Systems and Resources, School of Forest Engineering and Natural Environment, Universidad Politécnica de Madrid, Madrid, Spain
[b] Northern Research Station, U.S. Forest Service, 1992 Folwell Avenue, Saint Paul, MN 55108, USA

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ABSTRACT

International organizations increasingly require estimates of forest parameters to monitor the state of and changes in forest resources, the sustainability of forest practices and the role of forests in the carbon cycle. Most countries rely on data from their national forest inventories (NFI) to produce these estimates. However, because NFI survey years may not match the required reporting years, techniques for updating NFI-based estimates are necessary.

The main aim was to develop an unbiased method to update NFI estimates of mean growing stock volume ($m^3$/ha) using models to predict annual plot-level volume change, and to estimate the associated uncertainties. Because the final large area volume estimates were based on plot-level model predictions rather than field observations, hybrid inference was necessary to accommodate both model prediction uncertainty and sampling variation. Specific objectives were to compare modelling approaches, to assess the utility of Landsat data for increasing model prediction accuracy, to select the most accurate method, and to compare model-based and design-based uncertainty components. For four monospecific forest types, data from the 2nd and 3rd Spanish NFI surveys together with site variables and Landsat images were used to construct models to predict NFI information for the year of the 4th NFI survey. Data from the 3rd and 4th surveys were used to assess the accuracy of the model predictions at both plot-level and large area spatial scales.

The most accurate method used a set of three models: one to predict the probability of volume removals, one to predict the amount of removed volume, and one to predict gross annual volume. Incorporation of Landsat-based variables in the models increased prediction accuracy. Differences between large area estimates based on plot-level field observations for the 4th NFI survey and estimates based on the model predictions were minimal for all four forest types. Further, the standard errors of the estimates based on the model predictions were only slightly greater than standard errors based on the field observations. Thus, model predictions of plot-level growing stock volume based on field and satellite image data as auxiliary information can be used to update large area NFI estimates for reporting years for which spectral data are available but field observations are not. Finally, variances of means are under-estimated unless hybrid inferential methods are used to incorporate both model prediction uncertainty and sampling variation. For the two forest types for which the two sources of uncertainty were of the same order of magnitude, the under-estimation was non-negligible.



## 1. Introduction

Recent decades have seen an increasing demand for forest information, at least partially in response to international agreements such as the Kyoto Protocol adopted in 1997. International organizations including the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Framework Convention on Climate Change (UNFCCC) require estimates of the state of and changes in forest resources with the aim of monitoring those

*Abbreviations:* NFI, National Forest Inventory.

* Corresponding author at: Dept. Sistemas y Recursos Naturales, Escuela Técnica Superior de Ingenieros de Montes, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain.

*E-mail address:* sonia.condes@upm.es (S. Condés).

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resources, the sustainability of forest practices and the role of forests in the carbon cycle (Vidal et al., 2016). This increasing demand is reflected not only in the number of parameters for which estimates are requested but also in the increasing frequency of required reports. For example, FAO's Forest Resources Assessment (FRA) assesses the world's forests at 5- to 10-year intervals, while the UNFCCC requires annual reports (Ellis and Moarif, 2015).

National forest inventories (NFI) are the primary sources of information for producing reliable forest-related estimates with associated measures of uncertainty for basic forest attributes of which growing stock volume and forest area are the most common (Tomppo et al., 2010; Vidal et al., 2016). However, because many NFIs were designed with re-measurement cycles longer than the required reporting frequencies, the use of NFI data for responding to the requirements would entail either a revision of NFI protocols (Fridman et al., 2014) or use of prediction techniques to extrapolate NFI-based estimates to the assessment years. As an example, the question of how much woody biomass is available in Europe, which is relevant not only for developing realistic targets for the use of renewable energy sources but also to develop climate change mitigation strategies, is frequently addressed using empirical growth models (Cienciala et al., 2008; Barreiro et al., 2016).

Not all countries, especially those in the Mediterranean region, have well-developed projection systems with models applicable at national scales for all their forest types; more typically the models are restricted to specific species in highly productive regions (Barreiro et al., 2016). Moreover, reliable projections should take into account not only gross annual increment but also additional components such as natural losses and fellings (Tomter et al., 2016). In Europe, fellings are frequently predicted using past estimates of removals or scenario analyses (Salas-González et al., 2001; Barreiro et al., 2016; Tomter et al., 2016) which may or may not accurately reflect future conditions (Nabuurs et al., 2007).

When lengths of inventory re-measurement cycles exceed required reporting frequencies, as is the case for the Spanish NFI (SNFI) for which plots are only re-measured every 10 years, satellite data can be useful for predicting forest changes during the intervening years (González-Alonso et al., 2006). Satellite sensors such as Landsat provide valuable information for a wide variety of ecological applications (Cohen and Goward, 2004). Indices calculated from satellite spectral data have been instrumental in the development of modelling frameworks for detecting harvests (Healey et al., 2006) and forest changes (Hayes and Cohen, 2007) and for estimating biomass and other stand variables (Lu et al., 2004; Boisvenue et al., 2016).

When NFI sample plot data are the only source of forest information, design-based estimators are typically used (Ståhl et al., 2016). Because precision criteria often cannot be satisfied using only sample plot data, auxiliary information in the form of remotely sensed data are frequently used to enhance the estimation process by reducing variances. Common approaches include using models based on a combination of sample plot observations and the remotely sensed auxiliary data to predict an attribute of interest. These model predictions can then be used to construct strata for use with design-based, stratified estimators or they can be used directly with design-based, model-assisted regression estimators (McRoberts, 2010; McRoberts et al., 2013).

When observations for the sample plot locations for the time period of interest are not available, models are used to predict forest attributes for those locations. For such cases, uncertainties associated with the model predictions should be incorporated to ensure that the variance estimators are unbiased. Failure to acknowledge and incorporate the uncertainties associated with the model predictions is not uncommon, but of necessity leads to under-estimating the variances of population parameters, which may lead to poor decisions. Methods for incorporating uncertainty from both modelling and sampling sources into variance estimators for population parameters are characterized as *hybrid inference* (Corona et al., 2014; McRoberts et al., 2016; Ståhl et al., 2016). The primary features of hybrid inference are a probability sample of population units, but model predictions rather than observations for the attribute of interest for those sample units. The models are typically constructed using data either external to the spatial region of the sample or, in the case of updating NFI estimates, external to the temporal timeframe of the sample. Characterization of these methods as hybrid inference arises from the need to use model-based inferential techniques to estimate the component of uncertainty due to the use of model predictions rather than observations, and design-based inferential techniques to estimate the uncertainty component due to probability sampling rather than conducting a complete census of the population.

The primary objective of the study was to develop an unbiased method for updating estimates of NFI mean growing stock volume ($m^3$/ha) using models based on data from previous inventory cycles to predict annual plot-level volume change, and to estimate the associated uncertainties. The framework for the study was hybrid inference to accommodate both the model-based and design-based inferential components. Multiple prediction methods based on field, climatic, topographic, and Landsat-based independent variables were used to predict annual volume change, $\Delta V$. The specific technical objectives were i) to compare multiple updating methods with respect to both plot-level prediction accuracy and large area estimates of future mean growing stock volume and to select the most accurate method, ii) to assess the utility of Landsat data for increasing model prediction accuracy and the precision of the population parameter estimator, and iii) to compare the relative magnitudes of the model-based and design-based uncertainty components.

## 2. Materials and methods

### 2.1. Data

#### 2.1.1. Sample plot data

From its 2nd survey beginning in 1986, the Spanish National Forest Inventory (SNFI) has been a continuous inventory featuring a systematic sample of permanent plots located at the nodes of a 1-km square grid and remeasured using an approximate 10-year inventory cycle. Sample plots are concentric with 5-, 10-, 15- and 25-m radii for which diameters and heights of all trees with breast-height diameters of at least 7.5, 12.5, 22.5 and 42.5 cm, respectively, are measured. Allometric models are used to predict individual tree volumes which are weighted to accommodate the different concentric plot radii to predict total plot growing stock volume and aggregated to produce plot-level growing stock volume estimates.

The analyses focused on four monospecific forest types located in two Regions of Spain where the 2nd, 3rd and 4th SNFI surveys have been completed (Table 1): *Pinus halepensis* Mill. in the Region of Murcia and *Fagus sylvatica* L., *Pinus sylvestris* L. and *Pinus radiata* D. Don in País Vasco (Fig. 1).

#### 2.1.2. Auxiliary site data

For each plot, topographic slope (Slp, degrees) obtained from 1:25,000 topographic maps in raster format (IGN, 2003) was used as a measure of terrain conditions. Mean annual temperature (T, °C) and annual precipitation (P, mm) were obtained from raster maps with a 1-km resolution for the Iberian Peninsula (Gonzalo Jiménez, 2010). The Martonne aridity index (Martonne, 1926) was calculated as M = P/(T + 10) and was used as a measure of