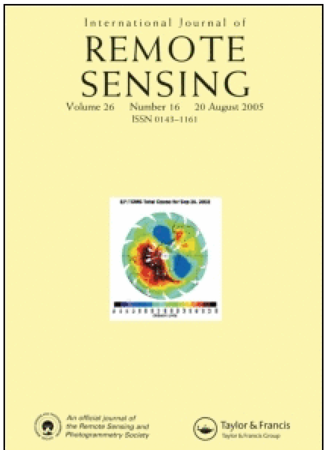

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Forest biomass estimation through NDVI composites. The role of remotely sensed data to assess Spanish forests as carbon sinks

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The present study is focused on the capabilities of remote sensing data and techniques to help in the monitoring of forest ecosystems as carbon sinks. It will attempt to find statistical relationships between satellite-derived NDVI (Normalized Difference Vegetation Index) data from SPOT-VEGETATION and NOAA-AVHRR and field measurements from the Spanish National Forest Inventory on the geographical basis of provinces. Statistically significant relationships were obtained when correlating the aforementioned datasets. These relationships were then used to predict forest biomass at a national level, in order to obtain updated forest information between consecutive National Forest Inventories.

1. Introduction

Spanish forest ecosystems have an extent of around 26 million ha, of which almost 15 million ha are covered by trees (29% of the Spanish territory), while the remaining are tree-less (23% of the Spanish territory). Coniferous, broadleaved and mixed forests cover 5.7, 5.2 and 3.9 million ha, respectively. The main broadleaved species in forested areas are *Quercus ilex* L., *Q. pyrenaica* Willd., *Q. suber* L., *Eucaliptus* spp. and *Fagus sylvatica* L., while *Pinus halepensis* Mill., *P. pinaster* Ait. and *P. sylvestris* L. are the main coniferous species. Adequate monitoring and management of forest resources seems necessary in order to meet the commitment to reduce greenhouse gas emissions under the Kyoto Protocol.

The intention of the Kyoto Protocol is to limit or reduce CO_2 and other greenhouse gases by an average value of 5% of 1990 levels in the commitment period 2008–2012 (UNFCCC 2006). The assimilation of atmospheric CO_2 by the Earth's vegetation ecosystems, especially by forests which represent a long-term pool, is a very important component of the global balance of carbon. The vegetation pool gains carbon from productivity investment in its components (wood, bark, branches, leaves, etc.) and loses carbon because of aging, mortality, fire, etc. (Myneni *et al.* 2001).

The Kyoto Protocol came into force on 16 February 2005. The Protocol is an international and legally binding agreement that will need control and monitoring mechanisms for treaty verification. These mechanisms should be implemented on

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both a national and global basis in the very near future. For those aspects related to carbon accounting in the case of land use change (deforestation, reforestation or afforestation) or changes in forest productivity (changes in the amount of biomass), reliable systems will be a key point in order to reduce uncertainties in traditional practices. In this context, the remote sensing community seems to be very well positioned as (i) land cover change identification using remote sensing is widely applied (Richards 2003) and (ii) satellite data can be useful for the estimation of forest biomass (Tomppo *et al.* 2002, Dong *et al.* 2003).

Long-term NOAA (National Oceanic and Atmospheric Administration)-AVHRR (Advanced Very High Resolution Radiometer)-based studies carried out during recent years have shown a tendency for greater greenness, as measured by NDVI (Tucker 1979), correlated with inventory values at province level (Myneni *et al.* 1997, 2001, Dong *et al.* 2003, González-Alonso *et al.* 2003, 2004). In the case of Spain, ground data from the Second and Third National Forest Inventories (NFI2, 1986–1996, and NFI3, 1996–2006) also confirm an increase in the amount of both forest biomass and forested land.

In Spain, the National Forest Inventory (NFI) is updated every 10 years, which may be too long a period for forest management purposes. Satellite data can be useful to obtain updated cartography of forested land and estimations of forest biomass during this 10 year gap.

The objective of the present study is to advance the development of reliable remote sensing techniques that should help in the assessment of Spanish forests as carbon sinks. The study is based on the use of validated standard products (calibrated NDVI temporal series) available through the Internet, in order to show the usefulness of working with this sort of product.

2. Material and methods

The study area is the whole Spanish territory, and results were always obtained on the geographical basis of provinces. The work involved the use of (i) field data from the NFI2 and NFI3, (ii) the European land use database CORINE Land Cover (CLC2000) and (iii) remotely sensed data from the VEGETATION sensor on-board SPOT (Système Pour l'Observation de la Terre) and from NOAA-AVHRR. Image processing was carried out with ENVI 4.1 and ArcView 3.2, while statistical analyses were performed using Statgraphics Plus 4.1.

The stem volume data from the Forest Inventories ($m^3 ha^{-1}$) included: (i) NFI3 values from 19 provinces (available data so far, as the NFI3 is still incomplete), and (ii) NFI2 values from 48 provinces. These 48 provinces cover the whole of Spain, except for the Canary Islands, Ceuta and Melilla, which were not considered since satellite information was not available for them. NFI data were obtained from the Spanish Ministry of Environment (NFI 2006).

Satellite data consisted of calibrated NDVI temporal series from SPOT-VEGETATION and NOAA-AVHRR sensors. This index has shown a strong relationship with photosynthetic activity and other forest parameters (González-Alonso *et al.* 2003, 2004, Myneni *et al.* 1997, 2001).

NDVI data from SPOT-VEGETATION ("VGT-S10" product) were downloaded from VITO (Flemish Institute for Technological Research; VITO 2006). The calibration process followed by VITO (Free VEGETATION Products 2006) can be summarized as follows: (i) VEGETATION channels 2 and 3 are calibrated into reflectance values (reflectance value$=0.0005\times$digital number); (ii) pixels affected by clouds or water are flagged and excluded from further processing; (iii) top-of-atmosphere apparent reflectance values are obtained for the remaining pixels; (iv) maximum value composites (MVC) are obtained, selecting the maximum NDVI value at every pixel's position (corrected for atmospheric effects); (v) daily and 10 day synthesis maps are derived from the daily MVCs; and (vi) NDVI values are codified as Grey values [NDVI=(Grey value × 0.004)−0.1]. Ten-day synthesis maps were used in the present study.

The NDVI dataset from NOAA-AVHRR ("Vegetation Index NDVI (NOAA AVHRR) monthly maps" product) was downloaded from DLR (German Aerospace Center; DLR 2006). The calibration process followed by DLR (Data products in EOWEB 2006) can be summarized as follows: (i) AVHRR channels 1 and 2 are calibrated into reflectance values using the coefficients provided by the NOAA team (NOAA 2006); (ii) pixels affected by clouds or water are flagged and excluded from further processing; (iii) NDVI values are obtained for the remaining pixels; (iv) daily NDVI maps are composed based on the maximum value (MV) at every pixel's position; (v) weekly and monthly synthesis maps are derived from the daily MVs; and (vi) NDVI values are codified as Grey values [NDVI=(Grey value/317)−0.1]. No atmospheric corrections were applied to the NDVI data. Monthly NDVI maps were used in the present study.

The main characteristics for the two NDVI datasets are summarized in table 1. The two datasets were processed separately, and mean annual NDVIs were obtained (from 27 ten-day maximum NDVI composites per year for VEGETATION and nine monthly maximum NDVI composites per year for AVHRR). From these annual values, mean NDVIs for the study period were obtained (1998–2004 for VEGETATION and 1996–2004 for AVHRR).

CLC2000 was used to obtain forest cartography for the 48 study provinces, as it is the most updated and available official land-use cartography for the European Union, delivered by the European Environment Agency (CORINE 2006). A forest-land mask was made selecting the CLC2000 classes considered as forests in Spain (Broadleaved forest, Needleleaved forest, Mixed forest, Agro-forestry systems and Transition shrubland). This mask was applied to the mean NDVI files previously obtained. Finally, mean NDVI values for forested land for the study period were obtained for each province.

The following information was available to carry out the statistical analyses: (i) mean NDVI values for the period and IFN2 stem volume data (as independent variables) for the 48 study provinces; and (ii) IFN3 stem volume data for the 19 available provinces (as dependent variables). A prediction equation was performed with data from these 19 provinces, which would then be applied to the whole set of 48 provinces. Stem volume from the NFI3 and mean NDVIs for the period were related through simple linear regressions (SLR). Multiple linear regressions (MLR) were performed considering mean NDVIs and NFI2 data as independent variables

Table 1. Main characteristics for SPOT-VEGETATION (VGT) and NOAA-AVHRR (AVHRR) NDVI datasets.

	Period	Months considered	NDVI composites	Spatial resolution
VGT	1998–2004	February–October	10-day maximum	1000 m
AVHRR	1996–2004	February–October	Monthly maximum	1000 m

Table 2. Description of the applied regression analyses.

	Regression type	Independent variable(s)	Dependent variable
SLR	Simple linear	Mean NDVI for the period	NFI3 stem volume data
MLR	Multiple linear	Mean NDVI for the period NFI2 stem volume data	

to predict NFI3 values (table 2). These analyses were carried out separately for the two datasets (SPOT-VEGETATION and NOAA-AVHRR).

3. Results and discussion

The first significant result is that mean NDVI values for the study period from both sensors are highly correlated (R^2=96%), even though files have different characteristics (see section 2).

The R^2 (expressed as a percentage) and root mean square errors (RMSE expressed in $m^3 ha^{-1}$) for the SLR and the MLR are shown in table 3, as well as the fitting coefficients for the regressions. The fitting lines for the SLR using SPOT-VEGETATION and NOAA-AVHRR data can be seen in figure 1.

The obtained results were slightly more accurate for SPOT-VEGETATION. The R^2 values for the regression between NFI3 and NDVI data (SLR) are quite high at a 1% level of reliability, which indicates the strong relationship between forest parameters and NDVI mean values for the study period. Nevertheless, the RMSE is considered too high, as it is close to NFI3 stem volume values for some provinces. When NFI2 stem volume data are considered as auxiliary data, and are included in the regression as an independent variable (MLR), statistical parameters improve considerably, so MLR is considered more reliable than SLR.

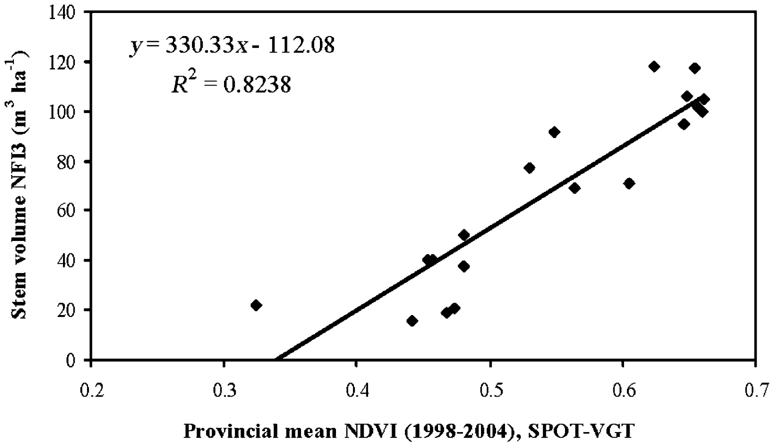
Prediction equations from MLR were applied to the whole set of 48 provinces, and predicted $m^3 ha^{-1}$ values per province were obtained. Predicted stem volumes (m^3) per province were then calculated using the forested areas from CLC2000 as expansion factors, and the increases over NFI2 on a provincial basis were obtained.

For the whole set of provinces within the NDVI range between 0.2 and 0.7, the mean relative error was an overestimation of 10.8% from SPOT-VEGETATION data, and of 14.1% from NOAA-AVHRR. The highest errors were obtained for provinces with stem volume under $30 m^3 ha^{-1}$. The provinces within this low range of biomass have a high percentage of forested area covered by "dehesas", a low-density forest type composed of major evergreen oaks. For the rest of the provinces, with stem volume over $30 m^3 ha^{-1}$, the errors are minor and acceptable.

Table 3. Results for the regressions obtained from stem volume data ($m^3 ha^{-1}$) and mean NDVI values from SPOT-VEGETATION (VGT) and NOAA-AVHRR (AVHRR).

	SLR				MLR				
	R^2	RMSE	*a*	*b*	R^2	RMSE	*a*	*b*	*c*
VGT	82.38	14.78	–112.08	330.33	95.73	6.86	−20.47	68.96	0.85
AVHRR	79.09	16.10	−94.44	388.78	95.24	7.24	−8.76	52.66	0.92

R^2 is expressed as a percentage, RMSE in $m^3 ha^{-1}$. Fitting coefficients for the SLR (simple linear regression) and MLR (multiple linear regression). *a* is the is the independent term, *b* is the coefficient associated to NDVI data and *c* is the coefficient associated to stem volume data ($m^3 ha^{-1}$) from the Second National Forest Inventory (NFI2).



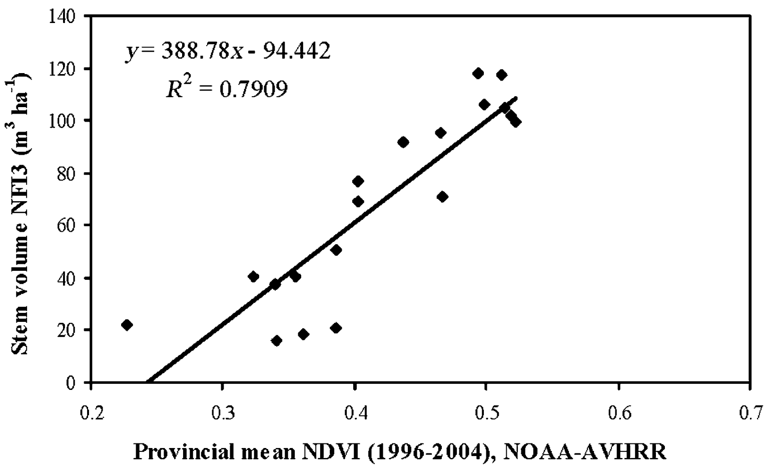


Figure 1. Fitting lines for the Simple Linear Regressions which correlate stem volume data from the NFI3 and mean NDVI values for the period from SPOT-VEGETATION and NOAA-AVHRR. Stem volume and NDVI data were obtained on the geographical basis of provinces.

The stem volume increase at a national scale was calculated using: (i) available NFI3 real values for 19 provinces; and (ii) estimated NFI3 values for the remaining 29 provinces. The national biomass increase over NFI2 (582712463.83 m^3) was 45.03% using VEGETATION data (845,117,963.76 m^3), and 45.58% using AVHRR (848,311,989.18 m^3). The stem volume increase over NFI2 for the 19 provinces with available NFI3 data is 48.30%, so figures obtained at a national level using the proposed methodology are quite close to those extracted from available ground information (NFI). These high increases between NFI2 and NFI3 can be justified not only because of the real increase in forest biomass, but also due to the use of different cartography for both inventories.

4. Conclusions

Forest biomass estimation at a national level through the use of two different temporal series of NDVI composites (from SPOT-VEGETATION and

NOAA-AVHRR) reveals a highly dependent relationship between satellite data and ground information from forest inventories. The obtained results were slightly more accurate for SPOT-VEGETATION.

These results reveal the interest of remote sensing techniques and data in order to assess and monitor forest resources as carbon sinks in the context of the Kyoto Protocol.

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