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ESTIMATING ABOVEGROUND BIOMASS IN NATIVE FORESTS USING REMOTE SENSING DATA COMBINED WITH SPECTRAL RADIOMETRY

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ABSTRACT

The management of forests as carbon (C) reservoirs could be a valid strategy for mitigating global climate change. In Salta, Argentina, there is an urgent need for updated information on biomass stocks in order to assess the C sequestering and release made by native forests. We studied three ecosystems (Chaco, Yungas and shrubland) by combining different data: a) field-estimated above-ground biomass (AGB); b) field-spectral data, and c) spectral data from remote sensing. AGB was estimated through allometric equations. Radiometric measurements were synthesized into a set of spectral vegetation indices (VI). The satellite data was calibrated with those obtained through field radiometry, allowing us to find a predictive AGB model which indicates an AGB average of 85 ± 250 $t.ha^{-1}$ for the center of the province of Salta. The model which was finally selected increases the level of estimate detail made at the national level and will allow the monitoring of such data.

Keywords: above-ground biomass; carbon stock; field radiometry; forest management; GIS; remote sensing.

ESTIMACIÓN DE BIOMASA EN BOSQUES NATIVOS USANDO DATOS DE SATÉLITE Y RADIOMETRÍA ESPECTRAL

RESUMEN

El manejo de bosques como reservorios de carbono (C) puede ser una estrategia válida para mitigar el cambio climático global. En Salta, Argentina, hay una urgente necesidad de información actualizada sobre el *stock* de biomasa para evaluar el secuestro y la liberación de C hecha por esos bosques nativos. Estudiamos tres ecosistemas (Chaco, Yungas y arbustales), combinando diferentes datos: a) biomasa (AGB) estimada por mediciones de campo; b) radiometría de campo y datos c)

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espectrales de sensores remotos. La AGB fue estimada por ecuaciones alométricas. Los registros radiométricos fueron sintetizados en índices de vegetación (VI) y los datos de satélite fueron calibrados con aquellos obtenidos por radiometría de campo. Construimos un modelo predictivo de AGB que indica un promedio de 85 ± 250 t.ha^{-1} para el centro de la provincia de Salta. El modelo finalmente seleccionado aumenta el nivel de detalle de las estimaciones realizadas a nivel nacional y permitirá el seguimiento de estos datos.

Palabras clave: biomasa aérea; *stock* de carbono; radiometría de campo; manejo de bosques; SIG; sensores remotos.

1. Introduction

The deforestation and degradation of biomass contribute significantly to increased global concentration of CO_2 in the atmosphere and, therefore, to the processes which are probably causing a change in global climate (IPCC, 2007).

Vegetation can act as a source of carbon (due to breathing, burning, degradation, deforestation, decomposition) and as a sink for atmospheric carbon (due to photosynthesis and plant growth) (Viglizzo *et al.*, 1997; Boschetti *et al.*, 2007). The processes involved in the storage and the release of carbon in space and time from terrestrial ecosystems (carbon represents 50% of the biomass, IPCC, 2000) are still little known in the world (Clark, 2007; Keith *et al.*, 2009).

Forests could be managed to mitigate greenhouse gas (GHG) emissions in the atmosphere (Dixon *et al.*, 1994) using three general strategies: i) maintaining or increasing carbon stock in existing forests; ii) creating new carbon stock by introducing new forests; and iii) replacing fossil fuels with biomass use (IPCC, 1996; Baral and Guha, 2004; Fang *et al.*, 2007).

Forests are complex, dynamic ecosystems, and maintaining ecosystem functions generates numerous goods and services of benefit to society (Masera *et al.*, 1997; MEA, 2005): regulatory functions; support and structure functions (Haygarth and Ritz, 2009); and information and provision functions (Holmlund and Hammer, 1999; De Groot *et al.*, 2002). These functions depend on the condition of the ecosystems, so that a less degraded ecosystem could provide better services and benefits than a more disturbed one (Kumar and Kumar, 2008). Some studies report that the biomass and carbon stock decreases markedly in secondary or degraded forests (Bonino, 2006; Sierra *et al.*, 2007; Ordóñez *et al.*, 2008), which can be reversed through timely planned management strategies (Thornley and Cannell, 2000; Kirschbaum, 2003; Jong *et al.*, 2007). The management of forests as carbon reservoirs could complement other environmental objectives including the protection of biological resources - water, soil, habitat, and raw materials, among others (Thornley and Cannell, 2000; Kirschbaum, 2003; Jong *et al.*, 2007).

In Argentina there are 33.2 million ha of native forests, including forest lands (lands with a crown cover of more than 20% of their surface and an area of more than 10 ha) and rural forests (forest remnants in an agricultural landscape, less than 1,000 ha) (SAyDS, 2005). 81% of Argentina's forest area is distributed between two phytogeographical regions (Cabrera, 1994): the

Chaco and the Yungas, which are at different levels of degradation (Montenegro *et al.*, 2005; Boletta *et al.*, 2006). In 2002, these formations were represented in the province of Salta with 5.6 million hectares of the Chaco and 2.3 million ha of the Yungas (UMSEF, 2005). Salta is one of the provinces with the highest rates of deforestation in the country. According to the Ministry of Environment and Sustainable Development of the Nation, between 2002 and 2006 the cleared area exceeded 400,000 ha (UMSEF, 2007). Even more serious was the situation in 2007, when the annual clearing reached an additional 435,000 ha (Paruelo *et al.*, 2011).

Exploring, understanding, quantifying and monitoring of the province's forest ecosystems is urgent in terms of the assessment of carbon sequestration services and plans for the best GHG mitigation strategies. Furthermore, this study and monitoring of forest AGB is urgent and necessary to ensure the maintenance of remaining ecosystem functions which take place (Lara *et al.*, 2009). The AGB is the major component of terrestrial ecosystem biomass (Brown, 1997). Some authors suggest that carbon sequestration is not the most important ecosystem function for local populations (Masera *et al.*, 1997), but identifying this ecosystem service will allow the planning and monitoring of comprehensive strategies based on carbon sequestration.

However, achieving this wealth of knowledge and information over large areas, such as those occupied by forest ecosystems in the province, requires expeditious methods which allow manipulation of large amounts of data, coverage of large areas, as well as monitoring and creation of projections in real time. Remote sensing is a suitable tool for measurements at different scales (local to regional) in a reliable, systematic form, affording us both current and historical records (Patenaude *et al.*, 2005).

Spectral records from sensors have shown good relationships with the biomass in different regions (Zheng *et al.*, 2004; Lu *et al.*, 2004; Anaya *et al.*, 2009). Also, good relations have been reported between field-estimated spectral records and different biophysical attributes of vegetation (Jia and Akiyama, 2005; Yang *et al.*, 2005; Grant *et al.*, 2007; Stroppiana *et al.*, 2009). Geographic information systems are now being used increasingly in the study of forest systems (Boschetti *et al.*, 2007; Anaya *et al.*, 2009; Fernández *et al.*, 2010). However, few bibliographic references were found for the combination of radiometric field records, AGB field survey and remote sensing data (Boschetti *et al.*, 2007).

This paper develops a reliable methodology which integrates the three types of data mentioned above in a Geographic Information System (GIS), which allows fast modeling of the AGB and carbon present in native forests, and the mapping of these stocks. The developed methodology, the database, and the biomass and carbon stock maps of the major native forests of the province presented herein, will enable planners and decision makers in the province to do appropriate monitoring to periodically update the database. The results obtained will enable design strategies for forest management to mitigate GHG, including other local development goals.

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2. Materials and methods

2.1. Study area

This work was conducted in the Lerma Valley, in the centre of the province of Salta, Argentina. The Lerma Valley has an area of 500,500 ha and is a fertile and highly-productive region. The three most represented native ecosystems in the province of Salta (the Chaco, the Yungas and a third one which we call the "shrubland") occupy an area of almost 317,000 ha in the Lerma Valley. The Chaco environment (Serrano and Transition Districts, according to Cabrera, 1994) makes up 44% of this area; the Yungas cover 35% of the total number (Pedemontana Forest, Montana and Montane Forest Districts, Cabrera, 1994); and the rest (21%) corresponds to the formation of plant communities dominated by shrubs and bushes. These three ecosystems were studied in this paper. The field surveys and samplings took place in the municipality of Coronel Moldes, in the centre of the Lerma Valley, which represents 17% of the total area of the valley. The average altitude is approximately 1,100 meters above sea level (Núñez *et al.*, 2007). The climate in the region is defined as dry subtropical (Martyn, 1992). The average annual temperature is 17.5ºC, with average maximum and minimum temperatures of 25.3°C and 10.7°C, respectively (Arias and Bianchi, 1996).

2.2. Study Design

Samples were collected at random in each of the three previously defined environments. We used rectangular plots, each with an area of 100 m^2, and the number of plots was defined in terms of the variability observed in each environment, starting with a 9-plot pre-sampling with an error of 20% and a probability level of 90%. From this pre-sampling AGB was estimated and the total number of samples (69 plots) were defined. These plots were distributed as follows: 40% in the Chaco, 36% in the Yungas and 23% in the shrubland. The geographical coordinates of the vertices of each parcel were surveyed with a GPS (Global Positioning System).

Three types of data were surveyed:
a) Above-ground biomass (AGB);
b) Spectral signature from field radiometry; and
c) Spectral signature from remote sensing (Landsat 5TM).

Each is described in more detail in the next section.

2.2.1. Above-ground biomass (AGB)

The structural variables of woody vegetation (diameter at breast height or DBH ≥ 1 cm and height ≥ 50 cm) recorded in the field were: stem height (from ground level to the first main branch, expressed in meters), total height (from ground level to the top of the crown, expressed in meters) and DBH (expressed in centimeters). The structural information obtained was used to estimate the

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AGB, which here refers to the total amount of living organic material of trees and shrubs ≥ 1 cm in diameter and ≥ 50 cm in height, expressed as dry weight tons per ha.

For each site, the biomass ($t.ha^{-1}$) of each plot was considered as the sum of the total AGB of the components or individual trees (kg), estimated through allometric equations (table 1). The equations used were proposed in the literature for similar ecosystems. The wood density data which is required in Equations 2 and 3 was obtained from the database compiled by INTI-CITEMA (2008). Where no data was available or species could not be identified, the WD used for the calculations were 0.766, 0.745, and 0.695 $t.m^{-3}$ for the Chaco, the Yungas and the shrubland, respectively.

2.2.2. Spectral signature from field radiometry

Spectral reflectance is the ratio between the flow of incident and reflected radiant energies, measured from an object or area in certain wavelengths (Peddle *et al.*, 2001). The spectral signature or reflectance of vegetation, defined as the capacity of vegetation to reflect electromagnetic energy in a certain wavelength (Pinilla, 1995), was recorded in two different ways: i) in the field, using a manual radiometer; and ii) from remote sensing using satellite imagery. In both cases, the obtained data was processed and handled as vegetation indices (VI).

The reflectance of vegetation was determined as the ratio between radiation reflected by the canopy and the incident radiation in the same time and place. The instrument used was a spectroradiometer LI-COR 1800, with a sensitivity of 0.3-1.1 μm, hemispheric reading and scan resolution of 2 nm. In this work the visible and near infrared wavelength range (from 400 nm onward), which covered approximately 66% of the total solar spectrum, only were processed.

In each sample plot (in its centre), there were two readings which we identified as a) and b): a) upward lenses to record global radiation at each site, which varies according to the altitude of the sun, the transparency of the atmosphere and the cloudiness (Pérez Priego, 2004); b) downward lenses (at a height of 2.5 meters from ground level). The readings were taken at the same time every day, from 10 to 14 hours, with a solar elevation angle over 75°, which sought to reduce the effect of the solar angle on the radiation reflected by the vegetation (Almeida *et al.*, 2007). The decision to take a single field spectral measurement by plot was based on data analysis carried out previously in a laboratory from a pre-sampling. In fact, for the first nine plots, three spectral field measurements were realized of each type of reading, by plot - taken at identical distances within a linear transect along the longest axis of the 100 m^2 plots-. However, by the type of hemispheric radiometer reading, records by plot showed no statistically significant differences among themselves. We decided to realize a record alone for plot, in the centre of the same one.

The analysis focused on the dry season, which runs from May to October in the region. The decision to work in this time of year was because cloud-free satellite images are available. Also, the central aim of the study was the natural ecosystems, and during the dry season, most of the rain-fed agriculture is in land preparation phase and is seen in the satellite images as zones devoid of vegetation differing more clearly from the natural vegetable coverage. On the other hand, much vegetation indices saturate at a given value of biomass (Fonseca, 2005), but if the biomass (as cover and foliage) is low, this does not happen. In deciduous environments, identification of the areal extent of each environment was verified by field surveys and analysis of a wet-season image.

Fieldwork was planned considering the date of capture of the satellite Landsat (every 16 days). Nine measurements were performed on September 7th, thirty measurements on October, 9th (both in 2008) and thirty measurements between these two dates.

2.2.3. Spectral signature from remote sensing radiometry

We used Landsat 5TM satellite images identified as path 231 and row 77 and 78, with Transverse Mercator Projection System and Datum SAD 69. Landsat images were provided by the National Institute of Spatial Investigations (INPE), in the Brazilian Department of Science and Technology. These images provide fine-scale data. The spatial resolution for all bands is 30 m, except for the thermal band (band 6), whose resolution is 120 m on the ground. This fine-scale data is needed to detect high levels of spatial heterogeneity expected in native forest ecosystems. Landsat images have allowed multispectral information required for the calculation of some comprehensive indices having a high temporal frequency. We worked with the image of October 9th, 2008.

The satellite images obtained were subject to basic adjustments or pre-processing. This pre-processing is necessary to adjust the data for use in quantitative analysis (Foody *et al.*, 2003) and it consisted of geometric and radiometric corrections. These are explained in the next section. The images were processed using Idrisi Kilimanjaro software.

2.2.4. Satellite images pre-processing

Scenes 231-077 and 231-078 were merged into a single mosaic. To remove the geometric distortion of satellite images, there was a correction using ground control points (GCP). We selected 18 GCP evenly distributed, available from a map of known projection and field data. Once the spatial interpolation was performed, we proceeded to determine the intensity value of the output image - interpolation of intensity or resampling. The resampling method used was the nearest neighbor. The Root Mean Squared Error (RMS) was < 1 pixel. The Reference System used for all satellite images and digital models was the Gauss Kruger Strip 3, Datum Campo Inchauspe. In the same geometric transformation process, the limits of the resulting image that covers the entire Lerma Valley were defined.

The radiometric calibration, performed by the module Radiance of Idrisi, consists of conversion of the digital numbers in radiance values considering calibration coefficients available for the satellite and the date used. To convert to radiance we used calibration factors (gain and bias) recommended by the U.S. Geological Survey (Chandler and Markham, 2003) captured after May 5th, 2003. The values of gains and bias are incorporated into the unit $mW.cm^{-2}.sr^{-1}.um^{-1}$.

The atmospheric calibration serves to reduce the effect of mist and gases. It was performed using the Atmosc module of Idrisi. After six out of seven Landsat bands were corrected (1, 2, 3, 4, 5 y 7), we proceeded to perform the atmospheric corrections using the Cost model designed by Chávez (1996), which is incorporated in the Atmosc module. This model estimates the atmospheric effect and partially corrects the data according to the position of the sun and the transmittance; since this represents the absorption by atmospheric gases and Rayleigh scattering, and was selected for data simplicity and setting (Chuvieco, 2006).

In addition to the gain and bias values, the Atmosc module requires the date and time of image acquisition, angle, and solar, satellite and average wavelength of the strip, to correct. The data-dependent scenes, date and sun angle, were obtained from the metadata file header of the same. For the dark object ND values were sought in the areas of known zero reflectance as deep water, in this case the Cabra Corral dam (Reservoir General Belgrano in the municipality of Coronel Moldes). For the satellite analysis of the samples from each environment, we extracted the reflectance in the red (band 3 of Landsat TM) and near-infrared (band 4 of the same sensor) bands of Landsat 5 TM.

2.2.5. Vegetation Indices (VI)

The spectral reflectance data is usually condensed into spectral vegetation indices (VI), which are mathematical transformations designed to measure the spectral contribution of vegetation in multispectral observations (Elvidge and Chen, 1995). These VI can be efficiently correlated with biophysical vegetation parameters (Zha *et al.*, 2003) and with biomass (Schino *et al.*, 2003; Foody *et al.*, 2003; Soenen *et al.*, 2010). Many VI have been used in remote sensing to estimate biophysical vegetation properties (Roy and Ravan, 1996; Boyd and Ibarrarán, 2002; Thenkabail *et al.*, 2002). Generally, these VI use red (RED) and near-infrared (NIR) bands, since 90% of the vegetation information is contained in these bands (Medeiros, 1987). The best known VI, widely used for monitoring natural biomes, is the Normalized Difference Vegetation Index (NDVI) (Tucker *et al.*, 1985; Sellers *et al.*, 1992). Its correlation with aerial net primary productivity has already been identified (Paruelo *et al.*, 2000, 2004; Piñeiro *et al.*, 2006). The NDVI is defined as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad 1)$$

Another widely used VI is the Ratio Vegetation Index (RVI), which is calculated as shown in the following equation (Jordan, 1969):

$$RVI = {}^{NIR}\!/_{RED} \qquad 2)$$

This index is often used in mountainous areas to minimize the effect of shadows (Boschetti *et al.*, 2007). Finally, the SAVI (Soil-Adjusted Vegetation Index) is a VI that incorporates a correction factor to compensate for the relative effect of the soil, and to take into account the observed amount of vegetation (Huete, 1988). Its formula is as follows:

$$SAVI = \left(\frac{NIR - RED}{NIR + RED + L} \right) \times (1 + L) \qquad 3)$$

These three indices: RVI, NDVI and SAVI were estimated in this paper. In the case of SAVI, the L parameter of the equation was used with a value of 1, according to Huete (1988). For the calculation of the VI we used the bands TM3 (630-690 nm) and TM4 (760-900 nm), respectively located in the RED and NIR regions of the electromagnetic spectrum. The crops areas or bare soils were masked in the subsequent processes of classification and analysis of the satellite image to avoid interference on the VI of native covers.

2.3. Data analysis

AGB and spectral (VI) data were used to derive and evaluate a set of predictive relations for AGB estimation from remote sensing. For all data, the correlations between AGB and VI, as well as those between the different VI (field and satellite), were assessed using the Spearman non-parametric test (for a significance level of p=0.01 and p=0.05). The data with more statistically significant relationships and higher correlation coefficient was selected to model the AGB in the Lerma Valley.

Three AGB predictive models were obtained, through which the distribution of AGB for the Lerma Valley and the corresponding frequency distribution histograms were simulated. For validation of the estimated AGB, we used 60 randomly selected independent field plots during the following year (2009), in the same season, located in different municipalities of the Valley. Field AGB data and AGB data estimated through each of the models were statistically analyzed using the Mann-Whitney test, for a significance level of p=0.05. This analysis allowed us to test and detect the model with the best statistical fit for the observed distribution of AGB in the Lerma Valley. We used the statistical software SPSS ver. 15.0.

3. Results and discussion

3.1. Vegetation indices: field radiometer

Table 2 shows the average above-ground biomass estimates (AGB) for each environment. AGB increases from the low values found in the shrubland environment (with extensive areas of bare soil and sparse vegetation), with intermediate values in the Chaco (with woody vegetation interspersed with grasslands), to maximum values in the environment of the Yungas (with a denser canopy than in the previous settings, and more than three vertical layers of vegetation). Some discussions and details of the factors operating in AGB manifestation can be seen in Manrique *et al.* (2011).

The relationships found between the VI obtained from records of field radiometry (and AGB data) are shown in table 3. In general, all VI show a strong relationship with the AGB variable. The sites with more vigorous vegetation or more vegetation cover (Yungas environment) present the highest values of RVI, NDVI and SAVI. Conversely, plots belonging to the shrubland environment present the lowest VI. All data shows a logarithmic behavior. The best fitting index proved to be the NDVI, as has already been indicated by other authors in the monitoring of vegetation (Piñeiro *et al.*, 2006; Julien and Sobrino, 2009). In contrast, Boschetti *et al.* (2007) indicates that the NDVI exhibits low fidelity with the above-ground biomass of mountainous grasslands.

Although many authors mention that the RVI and NDVI are not as effective as the SAVI, which allows adjusting the soil influence, the calculations above are much simpler, since they do not require the L parameter, which depends on an a priori knowledge of the study site in order to define it (Gilabert *et al.*, 1997). The results of this study show that the SAVI does not improve the ratios obtained, with respect to any of the other two indices; the best fitting AGB index in this case is the NDVI.

3.2. Vegetation indices: remote sensing

In a procedure similar to that used with the VI derived from field spectrum radiometry, the VI estimated from satellite images were correlated with the AGB values per plot (table 4).

The best relationship found between AGB and VI data obtained from satellite imagery shows r^2=0.74, which is lower than the values found for field spectral data (table 3), whose correlations appear to be highly significant ($p < 0.01$). This suggests that field radiometry allows better linkages with AGB data per plot than those which could be established only by using data from remote sensors (Ducati, 2000). Perhaps the improved adjustments are related to the accuracy of atmospheric correction. On the other hand, the spatial heterogeneity within the Landsat pixel should be considered (Milton *et al.*, 2007). Some authors have suggested that the field spectrum radiometry allows a greater control of measurement conditions and that it is the suitable technique for the study of relations between spectral parameters and information about the object (Ducati, 2001; Valeriano, 2003; Trishchenko, 2009). The results suggest that field radiometry could be a technique for further studies for remote sensing, both for basic research and for operational applications, and also might be useful as a tool for the development, refinement and assessment of models relating to biophysical attributes of the data obtained from remote sensors.

NDVI values obtained from a satellite image approximate those of bare soil. The shrubland, particularly, but also the Chaco ecosystem, in the dry season, show large areas of bare soil, because herbaceous cover is completely dry. Moreover, in both ecosystems there are a large number of small-leaved species, unlike the broad-leaved species in the Yungas ecosystem. The shrubland is dominated by deciduous shrubs like *Cercidium praecox, Acacia caven, Acacia aromo, Acacia furcatispina, Acacia praecox, Celtis spinosa, and Acanthosyris falcata*, among others. In the Chaco, there are semi-deciduous xerophilous species adapting to significant fluctuations in water availability like the herbivory. Among these species are *Castela coccinea*, alternating with deciduous species such as *Caesalpinia paraguarienses, Geoffroea decorticans, Gleditsia amorphoides*, and other evergreens such as *Aspidosperma quebracho blanco, Capparis retusa,*

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Capparis tweediana, Ziziphus mistol may be mentioned, as well as others. The Yungas is a forest dominated by evergreens (although there are deciduous species under study in the area). Some of the species in this sector are *Calycophyllum multiflorum, Phyllostylon rhamnoides, Tipuana tipu, Patagonula americana,* and *Eugenia mato.*

By comparing the NDVI values of field and satellite radiometry, the NDVI data from field radiometry shows higher values than those estimated from remote sensing, which can be seen in figure 1. This relationship may be reversed or changed in the wet season, which has yet to be studied. It would be desirable to replicate this study in a time series, including both dry and wet seasons. However, woody biomass (AGB) values are not altered between seasons since changes occur mainly in foliage, but not in the trunks of the trees (whose measurements are used in allometric equations for estimating AGB). While NDVI values may change in the wet season, the estimated field AGB values hardly change.

3.3. Biomass modeling

3.3.1. Method 1

We observed the relations between the AGB from the first nine plots (pre-sampling) and the NDVI derived from the satellite image. Considering the best adjustment of this index and the simplicity of its calculation, we proceeded to link the data of the NDVI with the AGB of each plot. The model found and applied to the image is shown in table 5 (model 1). The equation found between the values of NDVI and AGB is logarithmic (r^2=0.67).

Through this model, the frequency distribution histogram was obtained. The highest frequency of AGB values is in the range of 60-130 $t.ha^{-1}$. In particular, the category 101-111 $t.ha^{-1}$ occupies an area close to 80,000 ha in the Lerma Valley. The maximum AGB value estimated for the Valley through this model is 180 $t.ha^{-1}$ (figure 2). This distribution results in a lower range from that found for the AGB using allometric equations (table 2). In the assessment and verification of the model, the Mann-Whitney test reveals that there are no statistically significant differences (U=1,680 and p=0.067) between the AGB field data surveyed (60 plots) and the AGB data estimated through this model. Nevertheless, this model underestimates the AGB of the Valley.

3.3.2. Method 2

In this case, a radiometric data field to improve the fit between satellite image data and its relation to field data were used. The VI obtained through field radiometry was introduced into the analysis. In this case the NDVI also showed the best fit for the AGB of each plot.

The equation linking the AGB and NDVI data (from field radiometry), considering AGB as an dependent variable and NDVI as an independent variable, was used to estimate the values of the AGB from the satellite image. The model found is shown in table 5. Using this model, the average

AGB in the Valley is 60 $t.ha^{-1}$ (figure 2). The maximum AGB value estimated is 650 $t.ha^{-1}$, which is far from the maximum AGB value obtained for the area. The statistical test applied to the estimated AGB data (by model) and the AGB observed in the field indicates that there are significant differences between both sets of data (U=525.2 and $p<0.000$). This model must be improved since it does not have a good adjustment for field data and overestimates the biomass (AGB) of the Valley.

3.3.3. Method 3

As noted in a previous section, NDVI values from field radiometry are higher than those estimated from the satellite image. Therefore, if working directly with the equation found between field data (NDVI and AGB) to estimate the AGB from the image, the AGB mapping obtained is not suitable. Based on the previous model, which correlates the three types of data obtained for forest formations, we incorporated some modifications.

We estimate the magnitude of the difference between NDVI data from satellite and field, for the same plots. The average of the differences found between NDVI values was 0.31. The equation found between sets of data (NDVI field and image data) was $y=0.5161x+0.0204$ ($r^2=0.92$). This equation was used as an adjustment factor and was applied to the image to obtain a new series of NDVI data. AGB values were associated with this new series of NDVI data (calibrated with the field radiometric data). The new logarithmic model applied to the image is shown in table 5 (model 3).

The average AGB obtained by this method is 85 $t.ha^{-1}$, with a good distribution in each category. The maximum AGB value with this method is 353 $t.ha^{-1}$. The applied statistical test indicated that there were no statistically significant differences between the AGB values observed and estimated (using the model), with U=2,011 and p=0.86. While method 1, statistically, has a good adjustment to the AGB field values, it underestimates the AGB. Method 2 overestimates the AGB value and does not have a good adjustment. This method (number 3) overcomes both weaknesses and, statistically, has a good adjustment. We found a correlation coefficient of $r^2=0.8979$ (p=0.001) as shown in figure 3.

3.4. Final biomass mapping

Field radiometry is a useful technique to calibrate reflectance data from satellites. Method 3, which includes this calibration, approaches the values of AGB found in the field. This method and its corresponding model provide better adjustment than the other two methods and were applied to the satellite image previously treated. Consequently, a final AGB distribution map for the entire Lerma Valley was obtained. Since, on average, 50% of the biomass is carbon, with this model it was also possible to clearly estimate the distribution of fixed carbon in vegetation (IPCC, 2000) (figure 4).

The results obtained through this model were analyzed in relation to the area occupied by each cover type identified for the Lerma Valley, which can be seen in table 6. Further procedure details of the supervised and unsupervised classifications can be obtained from Núñez *et al.* (2007). The estimated AGB average values for the three environments were considered as reference values. On this basis, the other cover classes in the Valley were classified into three categories: i) zero biomass (0 t.ha^{-1}), ii) biomass between 1 and 35 t.ha^{-1} (average) and iii) biomass exceeding 35 t.ha^{-1} (high). About 50% of the Valley's area has biomass values that fall within the category of zero to average biomass (0-35 t.ha^{-1}). 26.51% of the total corresponds to the category of zero biomass (0 t.ha^{-1}), since they are bare soils, bodies of water, or infrastructure. Agricultural crops were also considered within this category and they were masked in the analysis to avoid disruptions in the estimated vegetation indices for natural forest biomass (coverage is of more interest for the purposes of implementing GHG mitigation strategies). 23.64% of the total corresponds to the category of the average biomass (about 119.000 ha), among which are: sparsely vegetated slopes, mountainous grasslands and shrubland/thickets. The remaining 50% of the surface corresponds to the category of the high biomass, with values exceeding 35 t.ha^{-1}. The range of the maximum biomass in the region of the Chaco (shown in yellow in figure 2) is up to 100 t.ha^{-1}, and in the Yungas (shown in greenish-blue in figure 2) it is up to 300 t.ha^{-1}.

Model 3 corresponds closely to the situation in the Lerma Valley analyzed from the classes of vegetation cover identified within it (Núñez *et al.*, 2007).

These are the first results obtained for the province of Salta, using a technique of field radiometry for this type of estimating and the first study that combines triple data logging (above-ground biomass, field radiometry and remote sensing radiometry). We recommend that complementary studies in other forest formations in the province of Salta be carried out before extrapolating the results found in this paper.

3.5. Importance of the estimates in the context of climate change

While in the primary sector GHG emissions globally are from the use of fossil fuels (70% of global CO_2 emissions from transport, industry, buildings, etc.), the second sector is "LULUCF" (Land Use, Land-Use Change and Forestry) with about 18 % global emissions; the sector includes deforestation and degradation of biomass. Since approximately 50% of the biomass of a forest or woodland ecosystem is carbon, burning or degradation emits that C into the atmosphere and contributes to global warming. The CO_2 with an annual growth rate of 0.4%, is the main GHG (McKeown and Gardner, 2009), accounting for about 80% of the increased greenhouse effect. Its concentration is more than 200 times that of the next GHG (CH_4) (measured in parts per million by volume).

The role of native forests is of great importance in the context of climate change, not only as carbon reservoirs, but also as providers of ecosystem goods and services, undoubtedly enabling the survival of the world's population directly (goods) or indirectly (ecosystem services). The forests in the province of Salta, which has 23% of the national forest area, mainly in the Chaco and the Yungas formations, are subject to an intense process of transformation and degradation, mainly due to the expansion of the agricultural frontier. The deforestation rate is three times the world average.

The results obtained in this study give us the information that carbon sequestered in the aboveground biomass ranges is between 17.5 -50 $tC.ha^{-1}$ in the Chaco; 17.5-150 $tC.ha^{-1}$ in the Yungas, and less than 5.17 $tC.ha^{-1}$ in the shrubland. For the Yungas, the C of the aboveground biomass mean is 47.9% of the total C in the fixed ecosystem. The case of the Chaco implies 32.8% of C, while in the case of the shrubland; it is only plotted for 19% of total C sequestration in this environment, as per local references (Manrique et al., 2011; Manrique and Franco, 2012). Considering the total area in which these forests are spread in the Valle de Lerma (over 300,000 ha), we can estimate that CO_2 sequestration in the aboveground biomass is nearly 44 million tCO_2. Assuming that the average Argentine citizen has a CF (Carbon Footprint) of 5.71 tCO2eq.yr-1 (SAyDS, 2008), for the entire population of the Valle de Lerma in calculations (approximately 580,000 people), it could be assumed that the annual emissions of the population are on the order of 3.3 million tonnes of $CO_{2eq}.yr^{-1}$. The forests studied, representing more than 60% of the total area of the Valley, could "compensate" for 13 years of the considered inhabitants emissions when stored over time.

This methodology, which can be easily replicated, allows us to observe the AGB and carbon distribution at the Valley level, and will enable its continued monitoring and updating. Not only carbon sequestration, but also various ecosystem functions that depend on the condition of woodlands, can be enhanced by using this information and tool for the development of planned management schemes. Other applications, for which this method will be useful, are: modeling of the standing timber volume per hectare for each ecosystem; calculation of the basal area of woodlands in different areas of the Lerma Valley; estimates of carbon emission due to the advance of cleared areas or the degradation of biomass and bioenergy distribution from natural biomass.

4. Concluding remarks

For the surveyed environments in the Lerma Valley, spectral records from field radiometry are an important source of input to calibrate the spectral records obtained from satellite images, in order to have better adjustments to the aboveground biomass of each site.

NDVI is the index that best explains the relationships between AGB and vegetation reflectance. The satellite data was calibrated with those obtained through field radiometry, allowing us to find a predictive AGB model and its corresponding distribution map, which indicates that the AGB for the Lerma Valley (Salta) ranges between 0 and 353 $t.ha^{-1}$, with an average of 85 $t.ha^{-1}$.

The AGB ranges between 35-100 $t.ha^{-1}$ in the Chaco, 35-300 $t.ha^{-1}$ in the Yungas, and less than 35 $t.ha^{-1}$ in the shrubland. The use of remote sensing techniques (field and satellite) and ground surveys combined in a Geographic Information System enabled us to obtain a model for AGB estimating and mapping of the entire Lerma Valley.

The results allowed us to estimate that the permanence of forests studied at the site, enable the avoidance of emissions of about 44 million tCO_2 sequestered, found only in the aboveground biomass.

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The obtained model, the collected database, and the resulting biomass and carbon maps will be useful tools for planned exploitation and management of the Lerma Valley woodlands, with GHG mitigation objectives which may, in turn, include other local development goals.

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TABLES

Table 1. Allometric equations used to estimate above-ground biomass (AGB). D = dbh (cm); ρ and S = wood density (g.cm^{-3}); H = total height (m); BA = basal area (cm^2); Y = tree biomass (kg).

Ecosystem	Equation	Number	Reference
Shrubland	$Y = 10^{\{-0.535 + 0.9996(\log 10 BA)\}}$	(1)	Martínez Yrízar *et al.* (1992)
Chaco	$Y = 0.112 \times \left(\rho \times D^2 \times H\right)^{0.916}$	(2)	Chave *et al.* (2005)
Yungas	$Y = \exp^{\{-2.4090 + 0.9522 \times \ln(D^2 \times H \times S)\}}$	(3)	Brown *et al.* (1989)

Table 2. Aboveground biomass for each environment (in t.ha^{-1}). Results were obtained considering all individuals with DBH ≥ 1 cm and height ≥ 50 cm. The density and basal area are expressed in average values and corresponding standard deviation. Biomass values are expressed in average and range (minimum and maximum).

Site	Plots	Density (nº ind.ha^{-1})	Basal area (m^2.ha^{-1})	Biomass (t.ha^{-1})
Shrubland	15	2013.7 ± 729.7	8.6 ± 2.8	17.7 (1.5-34.1)
Chaco	26	1314.3 ± 382.5	13.7 ± 4.2	58.5 (17.5-92.0)
Yungas	23	1120.4 ± 522.5	22.3 ± 9.1	136.3 (21.8-302.6)

Table 3. Relations between field radiometry and AGB (y=VI y x=AGB). ** The correlation is significant at a 0.01 level (bilateral) according to Spearman's test.

Vegetation Indices	Type of relation	r^2	Equation
RVI	Logarithmic	0.885** ($p < 0.01$)	$Y = 0.364 \ln(x) + 0.465$
NDVI	Logarithmic	0.893** ($p < 0.01$)	$Y = 0.126 \ln(x) - 0.198$
SAVI	Logarithmic	0.861** ($p < 0.01$)	$Y = 0.102 \ln(x) - 0.233$

Table 4. Relations between AGB and VI obtained from satellite images. The correlation is significant at a 0.05 level (bilateral) according to Spearman's test.

Vegetation Indices	Type of relation	r^2	Equation
RVI	Logarithmic	0.711 ($p> 0.05$)	$Y=0.493 \ln(x) + 0.051$
NDVI	Logarithmic	0.749*($p=0.053$)	$Y=0.08 \ln(x) + 0.022$
SAVI	Logarithmic	0.723*($p=0.025$)	$Y=0.07 \ln(x) - 0.176$

Table 5. Derived models to assess and map AGB in the Lerma Valley. In all cases the sample size is 60 plots.

Model	Equation	r^2
1	$Y=120.79 \ln(x) + 220.63$	0.673
2	$Y=6.3132\, e^{7.0561x}$	0.639
3	$Y=180.86 \ln(x) + 285.81$	0.761

Table 6. Thematic classes and area occupied by each of them.

Unit or Class	Area of the Valley (%)	Biomass potential values ($t.ha^{-1}$)
Natural watercourses	4,77	0
Dams and reservoirs	1,93	0
Agricultural plots	12,43	0
Airports and airfields	0,02	0
Urban areas	2,14	0
Bare soils and river beaches	5,22	0
Sparsely-vegetated slopes	4,45	1-35
Mountain pastures	5,78	1-35
Shrubland and scrubland	*13,41*	*1-35*
Chaco serrano and transition	*27,75*	*>35*
Subhumid Montano forest	*18,38*	*>35*
Humid Montano forest	3,72	>35
Total	100	

FIGURES

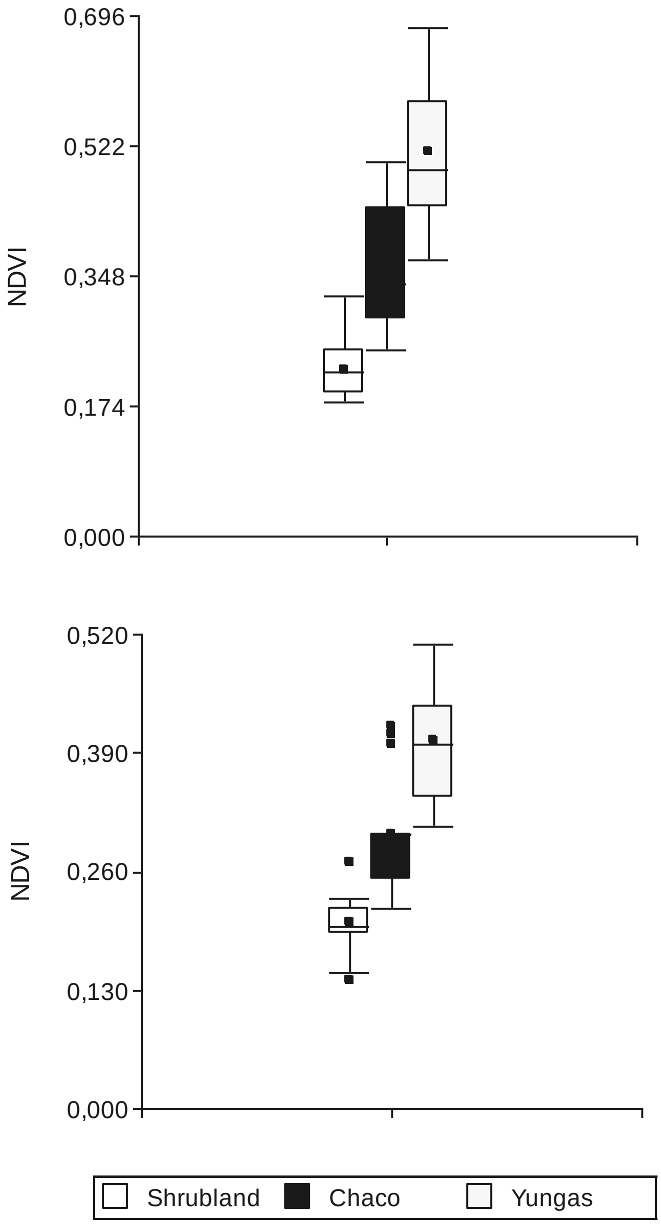
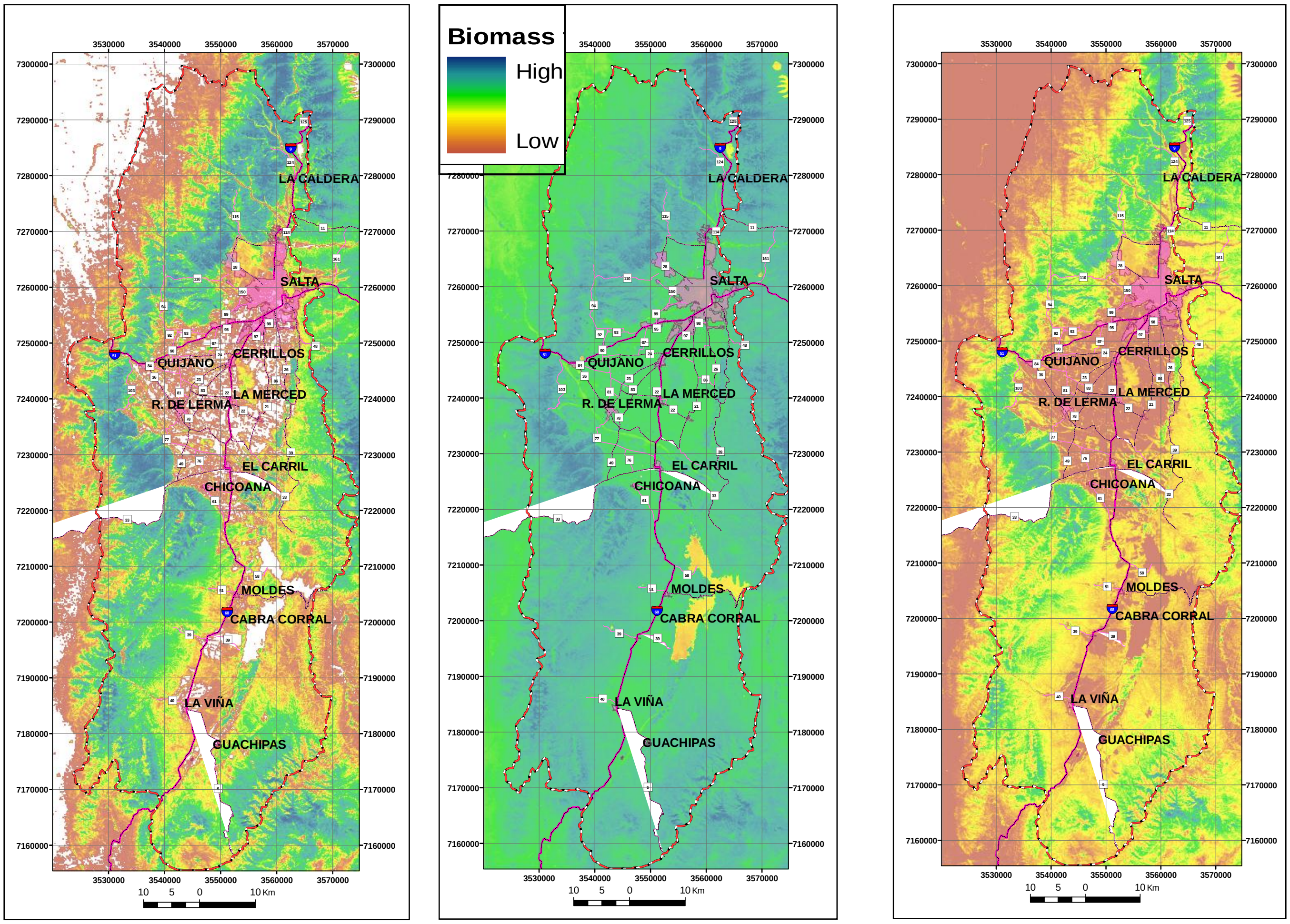


Figure 1. NDVI values estimated for shrubland, Chaco and Yungas from field spectral radiometry (top) and from remote sensing spectral radiometry (bottom).

(a) (b) (c)



Mean value: 74.2 t.ha^{-1}
S.D.: 46.3 t.ha^{-1}
Range: 0 – 180 t.ha^{-1}

Mean value: 65.6 t.ha^{-1}
S.D.: 84.1 t.ha^{-1}
Range: 0 – 657 t.ha^{-1}

Mean value: 85.4 t.ha^{-1}
S.D.: 51.2 t.ha^{-1}
Range: 0 – 353 t.ha^{-1}

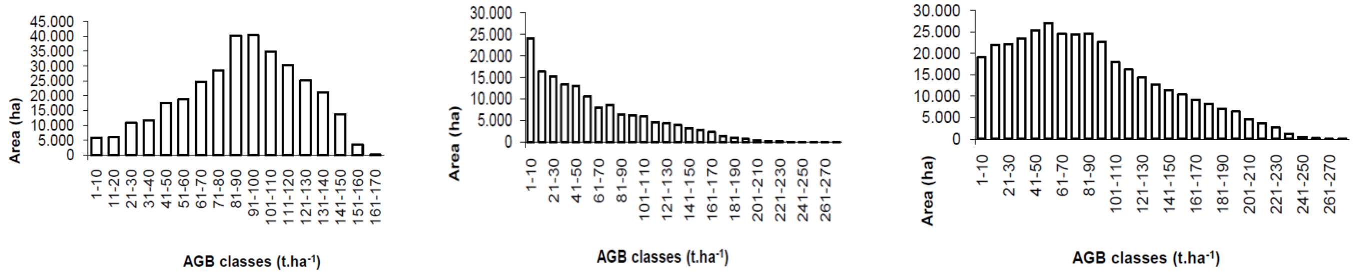


Figure 2. Top: Maps of AGB (t.ha-1) for (a) model 1, (b) model 2 and (c) model 3. Bottom: area represented in each AGB class. Indicates mean value, standard deviation (S.D.)

Manrique, S. M., Núñez, V. y Franco, J. (2012): "Estimating aboveground biomass in native forest using remote sensing data combined with spectral radiometry", GeoFocus (Artículos), nº12, p. 349-373. ISSN: 1578-5157

and range of values obtained of AGB. The histogram of model 2 has been cut in its upper classes of AGB.

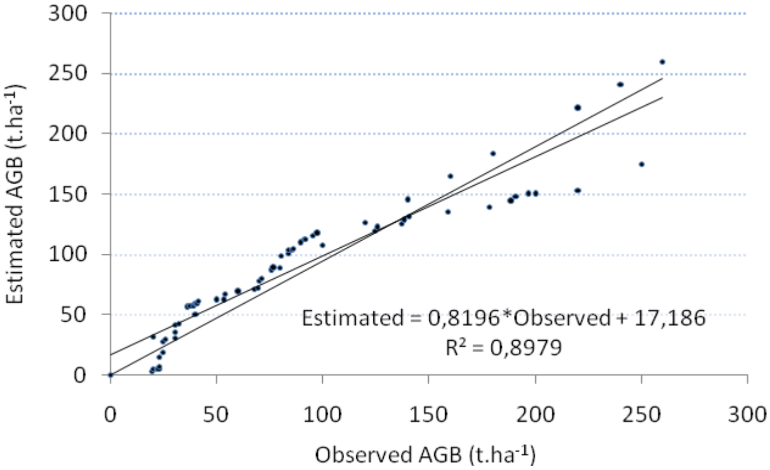


Figure 3. Estimated values of AGB (t.ha^{-1}) from the remote sensing-based (model 3) and the observed values of AGB calculated from field measurements (n=60, p=0.001). Each point represents the AGB for one of the 60 plots and the AGB for the pixel that the plot falls in.

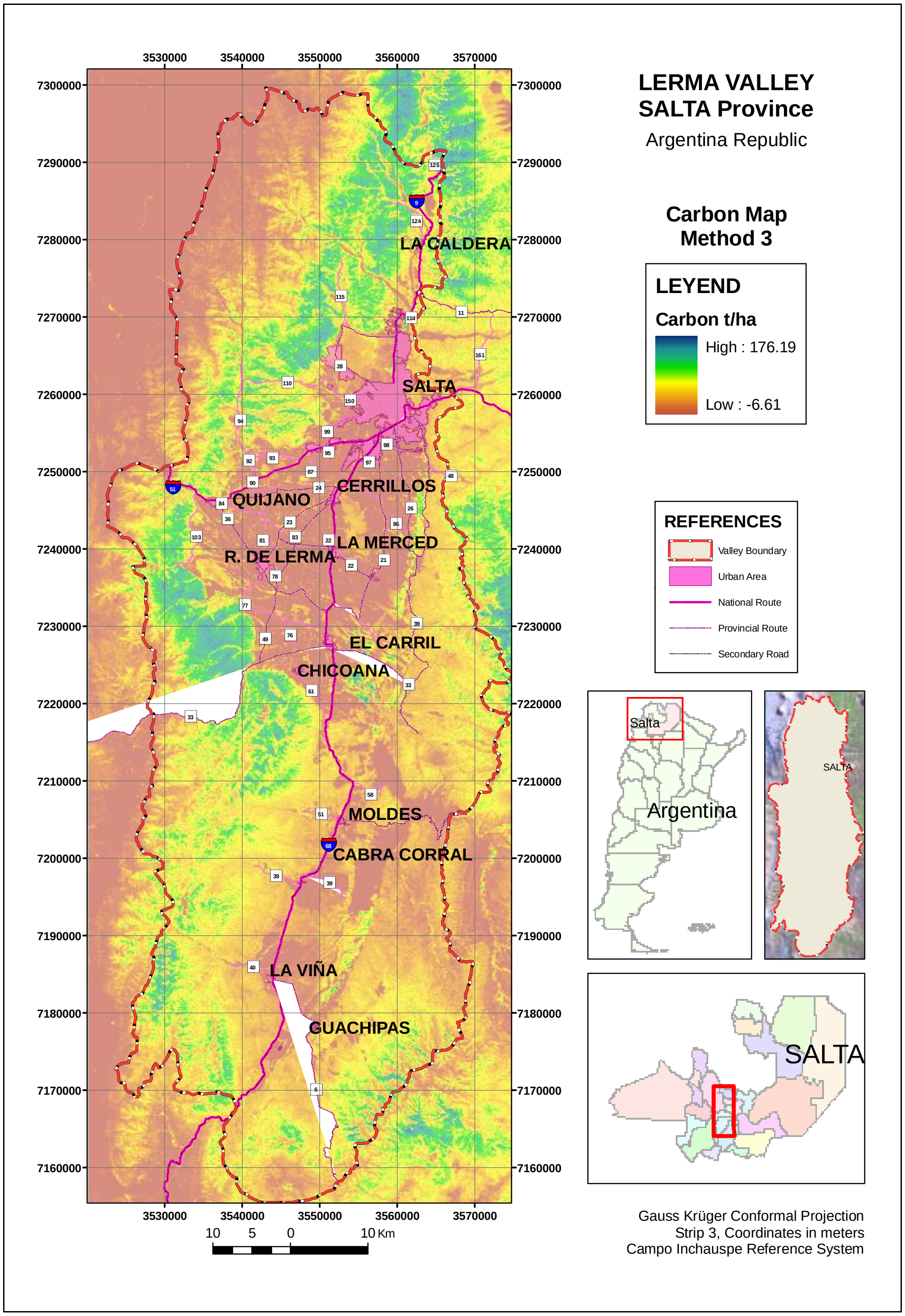


Figure 4. Distribution of fixed carbon in AGB. Method 3.