Journal of Arid Environments 74 (2010) 1262–1270

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Assessing multi-temporal Landsat 7 ETM+ images for estimating above-ground biomass in subtropical dry forests of Argentina

Néstor Ignacio Gasparri [a,*], María Gabriela Parmuchi [b], Julieta Bono [b], Haydée Karszenbaum [c], Celina Laura Montenegro [b]

[a] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) / Instituto de Ecología Regional (IER), Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán (UNT), C.C. 34, 4107, Yerba Buena, Tucumán, Argentina*

[b] *Unidad de Manejo del Sistema de Evaluación Forestal (UMSEF), Dirección de Bosques, Secretaría de Ambiente y Desarrollo Sustentable (SAyDS), San Martín 451, C1004AAI, Buenos Aires, Argentina*

[c] *Instituto de Astronomía y Física del Espacio (IAFE-CONICET), Ciudad Universitaria, C1428EGA, Buenos Aires, Argentina*

A R T I C L E I N F O

Article history:
Received 16 January 2009
Received in revised form
7 November 2009
Accepted 13 April 2010
Available online 20 May 2010

Keywords:
Above-ground biomass
Chaco
Dry forest
Regression model
Remote sensing
Vegetation index

A B S T R A C T

Above-ground biomass (AGB) is important to estimate total carbon pools in forests, where it has a key role in the global carbon cycle. We assessed correlations between spectral information and ground data to estimate AGB in the Semiarid Chaco, Argentina. Ground data (DBH, height and species of trees) were obtained from 15 samples (0.8 ha each) and AGB was estimated. Multi-temporal Landsat images were used to obtain spectral data (single bands/vegetation indexes) of the samples. Correlation tests between AGB and spectral bands and between AGB and vegetation indexes were performed for all dates. A strong correlation was found between spectral indexes and AGB in the early dry season (fall – May 12, 2002) while poorer results were obtained for summer and winter. This would result from a differential phenological response of trees, shrubs and grasses to environmental conditions. A biomass predictive model was fitted using the NDVI of May 12, 2002 and a biomass map was obtained applying this regression. There was a rain-related regional pattern of AGB decrease in an east–west direction, and a land-use related local pattern. Our results offer a great potential for increasing the understanding of dry Chaco forest structure and for improving carbon pools estimates.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Land-cover change is one of the major processes of global change (Foley et al., 2005). Among the drivers of land-use change, deforestation has received increasing attention because of its great impact on carbon cycling and biodiversity conservation (Achard et al., 2004; DeFries et al., 2002; Fearnside, 1997, 2000; Vitusek, 1994). Likewise, degradation of the forest by logging, cattle ranching and surface fires has a significant impact on its structure and function. This process occurs progressively and may not result in complete replacement of the native vegetation (Asner et al., 2005; Foley et al., 2007; Hougthon, 2005; Nepstad et al., 2003).

The dry forest is one of the most threatened ecosystems in the tropics and subtropics of the world because of deforestation and degradation processes and it has a small remnant area under protection (Hoekstra et al., 2005). Dry forests are mainly found on the American Continent (Miles et al., 2006), where human activities have resulted in a severely fragmented landscape characterized by a mosaic of secondary forests at different successional stages (Sánchez-Azofeifa et al., 2005). In South America, dry forests are present in major ecoregions such as the Cerrado in Brazil and the Chaco in Argentina, Bolivia, Paraguay, and in a small area in Brazil. These ecosystems are experiencing a drastic reduction in surface area due to expansion of the agricultural frontier (Grau et al., 2005a, 2005b; Klinck and Machado, 2005; Steininger et al., 2001; UMSEF, 2007), and degradation of remnant woodland patches by over-exploitation of natural resources and cattle ranching. The subtropical Chaco region, which covers a vast area (c. 1,200,000 km^2) (Dinerstein et al., 1995) including the largest continuous dry forest in South America (Eva et al., 2004), may represent the largest extra-tropical carbon stock in the Southern Hemisphere (Grau et al., 2005b).

In Argentina, the forests of the Chaco region cover an area of approximately 23 million hectares and include the southernmost subtropical dry forests in America. These are exposed to climate conditions different from those commonly defined for tropical dry forests (mean annual temperature above or equal to 25 °C; total

---

[*] Corresponding author. Tel.: +54 381 4255174.
E-mail address: ignacio.gasparri@gmail.com (N.I. Gasparri).

0140-1963/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaridenv.2010.04.007

annual precipitation between 700 and 2000 mm and three or more dry months every year) by the ecological research community (Sánchez-Azofeifa et al., 2005). In addition, large areas of the Chaco forest are located at latitudes higher than 22°S, thus being excluded from the global diagnosis recently performed for tropical dry forests (Miles et al., 2006). In consequence, land use cover change in Chaco forest received less attention than other tropical dry forests of America.

Dry forests in Argentina are currently undergoing high rates of land-use change due to the combination of market-oriented agribusiness and climatic change (Boletta et al., 2006; Gasparri and Grau, 2006; Grau et al., 2005a,b; Zak et al., 2004). Deforestation was estimated to be about 200,000 ha/year between 1998 and 2002 (UMSEF, 2007). For the Chaco forest, the average above-ground biomass (AGB) is 78 ± 7.9 Mg/ha, and calculations indicate a CO_2 emission from deforestation in the last decade of about 57,000 Gg/year, representing more than the emissions due to the Argentine fossil fuel consumption by transport (Gasparri et al., 2008). Since the AGB was estimated from the average value for the entire region, and the Chaco region shows a great variability in forest structure (e.g., tree cover ranges from 20 to 100%), this carbon emission estimate could be improved. Therefore, methods for assessing the structure of the dry Chaco forest such as biomass mapping are essential to accurately estimate biomass stock and carbon pool. Other authors also stated that remote sensing techniques for mapping and monitoring forest biomass provide more accurate estimates of forest condition and of carbon sources and sinks around the world (Dong et al., 2003; Hougthon, 2005; Lu et al., 2004).

In recent years there has been an increasing interest in relating biophysical variables of Neotropical dry forests to spectral information derived from medium- and high-resolution remote sensors (Arroyo-Mora et al., 2005; Costa et al., 2002; Feeley et al., 2005; Gillespie, 2005; Kalacska et al., 2005; Steininger, 2000). Many of these studies were performed in Central America where dry forests occupy less than 7 million ha (WWF, 2001), and focused on highly fragmented forests or on islands smaller than 10,000 ha. Additionally, these previous works commonly used a single date image in spite of the fact that the use of multi-temporal data improves the accuracy for monitoring biophysical variables (Dymond et al., 2002).

The dry forest in the Argentine Chaco differs from those in the rest of the American Continent in that it mainly comprises large areas of forest. On the other hand, differences in land-use history among countries determine differences in secondary forests. In Central America and the Caribbean, secondary forests result from the complete replacement of primary forests by agricultural or grazing lands, which are subsequently abandoned leading to forest regeneration, while those in the Argentine Chaco are in various states of degradation. Several activities are simultaneously carried out in the dry Chaco forest, such as extensive cattle ranching, short-term selective logging by forestry contractors and extraction of timber, firewood, charcoal and fence-posts either for the domestic or regional market.

In this context, the present work explores the use of Landsat 7 ETM+ images to estimate above-ground biomass in the Semiarid Chaco of Argentina. Multi-temporal data were used to include different phenological states. A possible correlation between spectral information and ground data for forests of different structure was investigated. Some regressions were evaluated to generate a map of AGB in the study area.

2. Materials and methods

2.1. Study area

The study area is located in the Chaco region (Semiarid Chaco subregion) in northwestern Argentina (between 23.5°S–27°S and 62.5°W–63.5°W) and encompasses the provinces of Santiago del Estero, Chaco, Salta and Formosa (Fig. 1). It covers 63,000 km^2 and includes part of the largest continuum of forest in the country, locally called the Impenetrable.

The area is characterized by flat relief and soils formed by eolian and fluvial sediments from the main rivers (Teuco, Bermejito and Salado). Mean annual temperature ranges between 22 and 23 °C, with mean temperatures of 28 °C and 16 °C for the hottest (January) and coldest (July) months, respectively. The Impenetrable, with absolute maximum temperatures above 48 °C, is one of the hottest areas in South America. Annual rainfall is low (between 400 and 900 mm), with a strong pattern of monsoonal seasonality occurring mainly between November and March (Minetti, 1999).

The natural vegetation of the area is a subtropical dry forest dominated by *Schinopsis lorentzii* (Griseb.) Engl., *Aspidosperma quebracho-blanco* Schltdl. and *Bulnesia sarmientoi* Lorentz ex Griseb. associated with other species like *Ziziphus mistol* Griseb., *Caesalpinia paraguariensis* (D. Parodi) Burkart, *Prosopis alba* Griseb. and *Prosopis nigra* (Griseb.) Hieron. (Cabrera, 1976). The most common species of the highest stratum are perennial (*B. sarmientoi* and *A. quebracho-blanco*) and semideciduous (*S. lorentzii*), while those in the lowest one are deciduous (e.g., *Z. mistol*, *Prosopis* spp. and *C. paraguariensis*) (Giménez and Moglia, 2003; Hueck, 1978). The forest shows a considerable variation in tree basal area, ranging from 1 to 15 m^2/ha in accordance with the First National Native Forest Inventory of Argentina (SAyDS, 2007). The understory vegetation is dominated by shrubs or grasses and occasionally bare soil is exposed. The main economic activities are cattle ranching, often within the forest, and charcoal production for local use, while cultivation is limited by rainfall and restricted to a few areas.

2.2. Sampling design and field measurements

Ground data to estimate above-ground biomass were obtained from the First National Native Forest Inventory of Argentina performed in 2000 (SAyDS, 2007). Particularly for the Chaco region, the field inventory was based on a 50 km grid started in an initial point randomly selected. In each grid point, a ground sample consisted of a 10 m wide strip of a length of 800 m was established and species, height and diameter at breast height (DBH) were recorded for all trees with DBH equal to or greater than 10 cm. The ground samples were georeferenced from the starting and ending points (transect) and incorporated in a geographic information system (GIS). More detail about the sampling design and the field procedures of the First National Native Forest Inventory of Argentina in the Chaco region is in SAyDS (2005).

For this work, we used a subset of 15 ground samples that were located in the Chaco region in the area covered by Landsat scenes path 229 rows 77 and 78 (Fig. 1). The tree volume with bark was estimated using standard formulas (Sevola, 1975) and then, the volume per species per sample was calculated. The above-ground biomass per sample was estimated following the methodology of Brown (1997), and wood density data (oven-dry mass per unit of green volume) were obtained from the National Institute of Technology and Industry (INTI-CITEMA, 2008).

2.3. Image data and processing

Chaco ecosystems have very complex phenology requiring the multi-temporal analysis of spectral data to improve the accuracy of monitoring the vegetation in the region. A multi-temporal Landsat 7 ETM+ image dataset (path/row: 229/77 and 229/78) acquired at different dates (July 28, 2001; March 9, 2002; May 12, 2002;

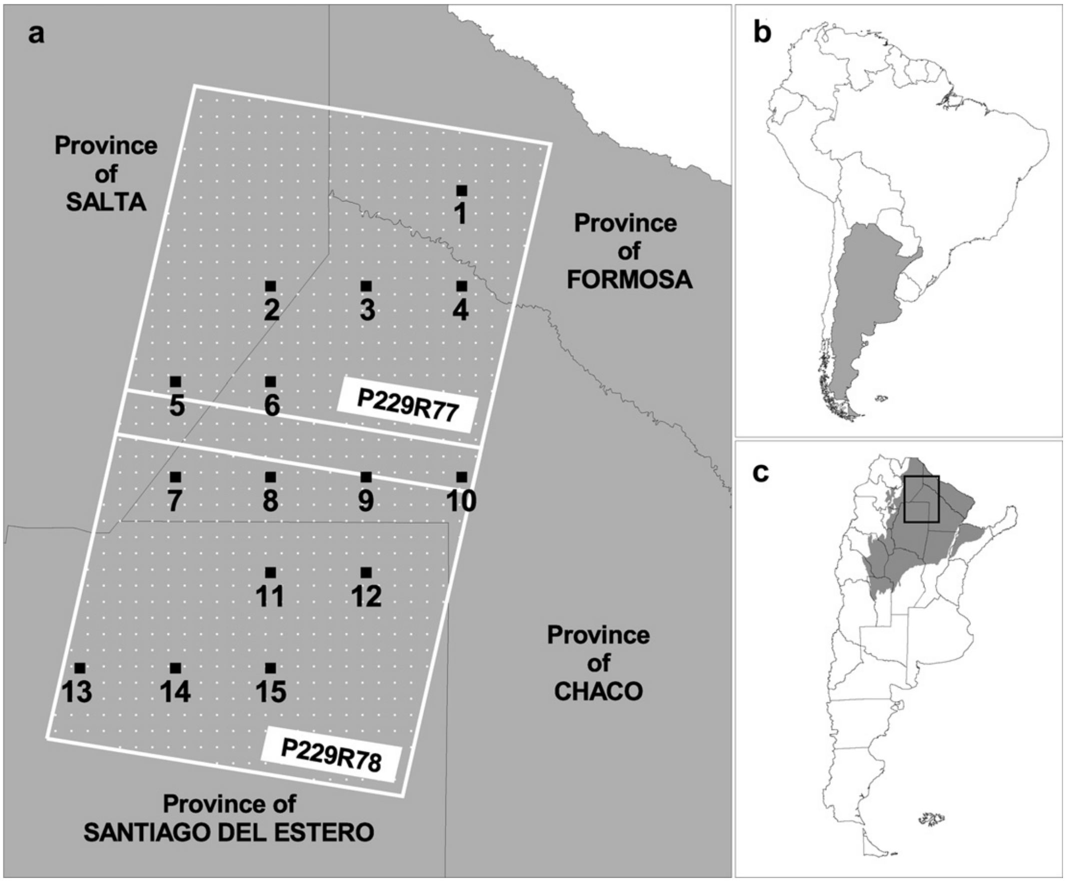

Fig. 1. (a) Study area (Landsat scenes plotted as white dotted squares) and ground samples, (b) Argentina in South America and (c) study area in Chaco region in Argentina. P: path, R: row.

February 24, 2003; April 13, 2003) was used. This set included different vegetation phenological states. Landsat 7 ETM+ images were used because they have spectral bands sensitive to biophysical attributes associated with forest, suitable spatial resolution for regional mapping (30 × 30 m) and useful temporal resolution (16 days) for monitoring phenological changes of vegetation.

Image preprocessing involved georeferencing and surface reflectance calculation. First, we georeferenced the images acquired on July 28, 2001 using orbital parameters and ground reference points geolocated with a Global Positioning System (GPS). These images were used as reference to co-register the other images. For this purpose, 50 control points were collected per image and a first order polynomial function with an error less than one pixel (30 m) was applied using the nearest-neighbor resampling method. We used the official projection system for Argentina (Gauss-Krüger Conformal Projection, Datum WGS 84). The surface reflectance of all images was calculated applying Rayleigh atmospheric correction (Kaufman, 1989), and then a multiplying factor (500) was applied to rescale images to 8 bits. The following vegetation indexes were calculated: Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI) and Normalized Difference Moisture Index (NDMI). The NDVI is a well-known index that shows good relationships with vegetation characteristics such as above-ground biomass, green biomass and chlorophyll content (Tucker, 1979). The NDVI combines red (RED) and near-infrared (NIR) bands according to the equation $\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED})$. The SAVI, which was proposed by Huete (1988) to minimize spectral variance due to background soil type, is calculated as: $\mathrm{SAVI} = (1 + L) \times (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED} + L)$, where $L = 0.5$ in order to reduce soil effect for vegetation with intermediate density. Lastly, the NDMI is sensitive to soil moisture (Wilson and Sader, 2002) and vegetation moisture (Freitas et al., 2005), and combines the near-infrared (NIR) and mid-infrared (MIR) bands; it is calculated as $\mathrm{NDMI} = (\mathrm{NIR} - \mathrm{MIR})/(\mathrm{NIR} + \mathrm{MIR})$.

Finally, the ground samples were imported into a GIS and a 50-m buffer area was generated around each transect. These areas were used to select spectral samples (mean reflectance of each Landsat 7 ETM+ band except for the thermal-IR band) and index samples (mean of NDVI, SAVI and NDMI).

All procedures were performed using ArcView GIS 3.2a and ERDAS Imagine 8.5 software.

2.4. Biomass estimation and mapping

Empirical models are important tools for relating field-measured biophysical variables to remote sensing data (Cohen et al., 2003). First, for all dates, the correlations between AGB and spectral bands, as well as between AGB and the vegetation indexes were evaluated by the non-parametric Sperman's test (Zar, 1999). Then, the date with stronger correlations was selected to perform several regression analysis to explore the relationship between biomass and spectral data through two different approaches: (a) step-wise regression method (Ordinary Least Squares) to compare linear models based on a single band or multiple bands, and (b) linear, quadratic or non-linear (exponential and logarithmic) models, based on vegetation indexes successfully used in previous studies (Lawrence and Ripple, 1998; Steininger, 2000). The regression models were evaluated using the *F*-test, the correlation

Table 1
Ground samples' location and estimated forest structure parameters. Source: First National Native Forest Inventory of Argentina (SAyDS, 2007).

Ground sample	Geographic Coordinates (Datum WGS84)		Basal area (m^2/ha)	Density (trees/ha)	Volume with bark (m^3/ha)	Above-ground biomass (Mg/ha)
	LAT S	LONG W				
1	24°04′	61°39′	2.7	83	5.2	54.6
2	24°32′	62°38′	12.2	265	30.2	135.0
3	24°32′	62°08′	5.4	238	11.3	79.4
4	24°32′	61°39′	10.4	198	24.8	101.3
5	24°59′	63°08′	5.9	125	15.3	92.5
6	24°59′	62°38′	4.6	74	14.7	93.3
7	25°26′	63°08′	8.1	199	17.4	99.4
8	25° 26′	62°38′	7.2	221	17.6	103.0
9	25°26′	62°08′	7.6	163	18.3	103.5
10	25°26′	61°38′	9.3	191	24.7	122.6
11	25°53′	62°38′	5.5	155	15.1	92.1
12	25°53′	62°08′	9.4	241	29.8	132.6
13	26°20′	63°38′	4.6	216	13.2	86.2
14	26°20′	63°08′	8.5	233	26.9	125.4
15	26°20′	62°38′	6.6	236	21.6	113.0

coefficient (R) and the error (S). We selected one equation for mapping biomass by comparing the R values of the regressions obtained.

The biomass mapping procedure was performed by applying a Reduced Major Axis (RMA) linear model with the NDVI as independent variable. The RMA regression was fitted using specific software developed for this regression method (Bohonak, 2004). This model was applied to an area previously classified as forest according to a land cover map developed by the Forest Division, Secretariat for the Environment and Sustainable Development, Argentina (UMSEF, 2007). In this report a forest is defined as a land with tree crown cover of more than 20% and a minimum tree height of 7 m. This definition was adapted for Argentina from the one developed by the Forest Resources Assessment (FRA) program of the Food and Agriculture Organization (FAO). Regional and local patterns of forest biomass were explored on the biomass map obtained.

3. Results

For a better interpretation of remote sensing data in the study area, Table 1 summarizes the information on the forest attributes for each ground sample (tree basal area, density, volume with bark and above-ground biomass). For the 15 samples, basal area ranged between 2.7 and 12.2 m^2/ha and above-ground biomass between 54.6 and 135 Mg/ha, with a mean of 102 Mg/ha.

Fig. 2 shows the forest spectral signatures for each date provided by ETM+ bands (average of 15 samples). These spectral signatures revealed a common pattern for the dry forests of the Chaco region. In summer (February and March) and fall (April and May), spectral signatures in the visible spectrum displayed low values in bands 1 (BLUE) and 3 (RED) and a relative maximum in band 2 (GREEN) caused by chlorophyll absorption/reflection. In the infrared portion of the electromagnetic spectrum, band 4 (NIR) showed a high reflectance due to reflection from the internal leaf structure (mesophyll), while bands 5 and 7 (MIR) showed a decreasing reflectance as a result of water absorption. The difference between bands 4 and 5 was larger in summer and April. In winter (July) there was a change in the relationship between bands 4 and 5 and there was no relative maximum value in band 2, since the vegetation corresponds to a semi-deciduous open forest. The loss of green biomass during this season leads to a decrease in photosynthetic activity. Band 4 exhibited a seasonal variation, with higher values in the rainy season and lower values in the dry season.

Fig. 3 reveals the behavior of three vegetation indexes as a function of increase in AGB of ground samples for the different image dates analyzed. NDVI varied from 0.44 in winter (July) to 0.77 in late summer (March). NDMI showed negative values in July because values in band 5 were higher than those in band 4. It varied between 0.11 and 0.27 for the remaining dates. SAVI exhibited the lowest variation (0.17–0.37) between winter and summer. Both NDVI and NDMI tended to increase with increasing AGB in May, except for samples 2, 12 and 14.

Table 2 shows the correlation coefficients (R) between AGB and spectral values and vegetation indexes for the dates analyzed. On the basis that the image of May 12, 2002 showed stronger correlations than the other dates, particularly for bands 2, 3, 5 and 7, NDVI and NDMI, this date was selected to fit the AGB empirical model.

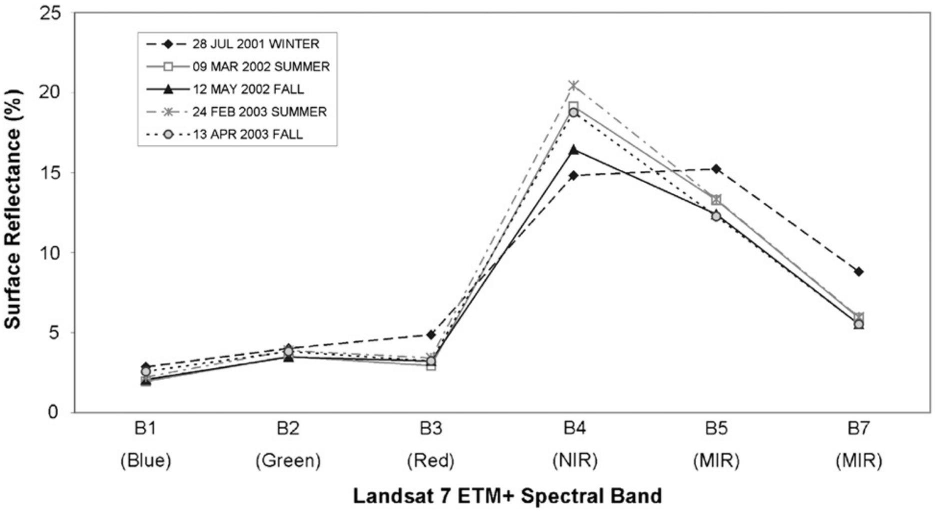

Fig. 2. ETM+ spectral signatures of forest (average of 15 samples) for each date expressed in reflectance (%) in the Semiarid Chaco subregion (NIR: near-infrared, MIR: middle-infrared).

Table 3 shows the regression models to estimate above-ground biomass. The stepwise procedure indicated that the best model was a single-band model using band 7 (Model 1), while the combination of bands did not improve the function. The NDVI linear, quadratic, exponential and logarithmic models (Models 4, 5, 6 and 7, respectively) yielded acceptable correlation coefficients. From the regressions that showed the highest *R* (NDVI equations), we decided to use a linear model because of its simplicity.

To perform the biomass map, we used a NDVI linear regression fitted by RMA because this method was indicated as more appropriated in remote sensing (Fig. 4). The RMA regression is a better method to estimate biophysical variables than the traditional Ordinary Least Squares because it makes no assumptions about relative amounts of measurement error of the independent variable. Additionally, RMA treats variables symmetrically and reduces the attenuation or amplification of estimates in extreme values of the dependent variable (Cohen et al., 2003).

Fig. 5 illustrates a map of above-ground biomass and forest extent. Although a value of AGB was obtained for each pixel, values were grouped into six intervals to facilitate their visualization (Fig. 5b). In this map, higher values of AGB are clearly seen to the east of the study area, where rainfall is higher, while low values

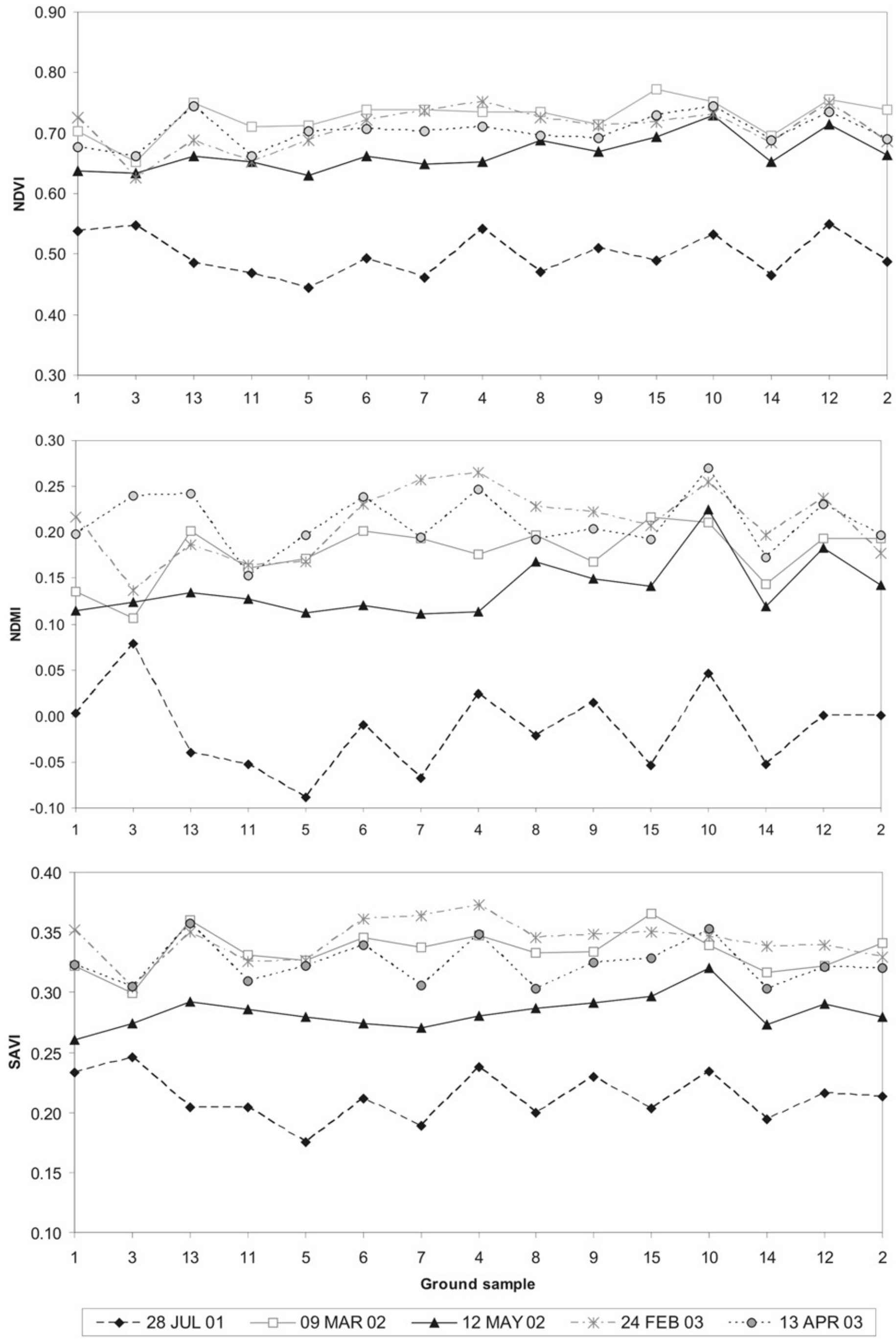

Fig. 3. Comparison of vegetation indexes (NDVI, NDMI and SAVI) of the forest ground samples at different dates in the Semiarid Chaco subregion. Ground samples are ordered following increasing biomass values in *X* axis. The date selected to estimate the regression model is indicated in solid black line.

Table 2
Correlation coefficients between above-ground biomass and spectral data/vegetation indexes per date in the Semiarid Chaco subregion.

Dates	Spectral bands						Vegetation indexes		
	B1	B2	B3	B4	B5	B7	NDVI	NDMI	SAVI
28 Jul 01	−0.200	−0.088	−0.144	−0.174	−0.159	−0.218	0.035	0.050	−0.050
09 Mar 02	−0.365	−0.541*	−0.497	−0.141	−0.574*	−0.465	0.465	0.347	0.144
12 May 02	−0.493	−0.514*	−0.614*	−0.057	−0.521*	−0.654**	0.559*	0.556*	0.203
24 Feb 03	−0.326	−0.453	−0.288	−0.338	−0.397	−0.356	0.191	0.276	−0.090
13 Apr 03	−0.597**	−0.629**	−0.421	−0.262	−0.182	−0.156	0.253	−0.121	−0.129

$^{*}P < 0.05$ and $^{**}P < 0.01$; B, spectral band of Landsat 7 ETM+.

appear to the west and intermediate ones in the center. Although agricultural lands are commonly found in the south-east, they are surrounded by high biomass areas. At the local level, low-biomass forests are found in restricted areas close to cattle ranches (about 7000 ha) and roads (Fig. 5c).

4. Discussion

The use of remote sensing techniques has proven to be a suitable tool for estimating above-ground biomass in the dry Chaco forest, which has some advantages over the tropical evergreen forest. In Chaco forest there is a better chance of getting cloud-free images and marked phenological cycles than in tropical evergreen forest, and thus providing more opportunities to assess vegetation attributes. This aspect was also pointed to dry forest in Venezuela (Feeley et al., 2005).

The significant correlation value obtained between NDVI and AGB using the images from May 2002 ($R = 0.559$, $P < 0.05$), is comparable to those obtained between NDVI and biomass in Brazil and Thailand (Foody et al., 2003), between NDVI and crown closure in Venezuela (Feeley et al., 2005) and between Landsat TM bands and biomass in Brazil (Steininger, 2000).

The relatively low biomass values in the dry Chaco forest account for the low reflectance values obtained for the NIR band. This overcomes the saturation problem of the NDVI, in contrast to what was reported for other areas with closed vegetation (Dong et al., 2003; Gilabert et al., 1997; Purevdorj et al., 1998).

Asner (1998) found a good correlation between the NIR band and above-ground biomass in savannas and woodlands in Mexico and Brazil. This does not agree with our results, possibly because the effect of bare soil in the sparse dry forest we studied may have decreased the accuracy of biomass estimation. However, the use of SAVI, which includes a constant soil adjustment factor (L), was not useful to improve correlations. A possible explanation is that in our study site there are not major variations in soil and SAVI only has advantages over NDVI when data are compared across different soil types (Huete, 1988). Although optimum values of L are affected by vegetation density, we decided to use the 0.5 value recommended for intermediate density because of its usefulness to reduce soil noise problems in a wide range of vegetation covers (Huete, 1988).

Table 3
Regression models to estimate above-ground biomass (AGB) using spectral data (Landsat 7 ETM+, 12 May 2002) as independent variable and field data (AGB) as dependent variable.

Model	R	S	F	P
1. $\mathrm{AGB} = 214.07 - 20.36\ \mathrm{B7}$	0.581	18.1	6.63	0.023
2. $\mathrm{AGB} = 222.52 - 37.50\ \mathrm{B3}$	0.560	18.3	5.95	0.030
3. $\mathrm{AGB} = 254.01 - 12.28\ \mathrm{B5}$	0.436	19.9	3.06	0.104
4. $\mathrm{AGB} = -211.65 + 470.26\ \mathrm{NDVI}$	0.636	17.1	8.83	0.011
5. $\mathrm{AGB} = -2423 + 7000\ \mathrm{NDVI} - 4810\ \mathrm{NDVI}^2$	0.663	17.2	4.72	0.030
6. $\mathrm{AGB} = 3.79\ e^{4.9\mathrm{NDVI}}$	0.613	17.3	7.86	0.014
7. $\mathrm{AGB} = 232.16 + 320.69\ \ln \mathrm{NDVI}$	0.640	17.0	9.01	0.010
8. $\mathrm{AGB} = 51.97 + 357.85\ \mathrm{NDMI}$	0.533	18.7	5.17	0.041
9. $\mathrm{AGB} = -35.95 + 1507\ \mathrm{NDMI} - 3547\ \mathrm{NDMI}^2$	0.564	19.0	2.80	0.100
10. $\mathrm{AGB} = 59.84\ e^{3.6\mathrm{NDMI}}$	0.504	18.9	4.42	0.055
11. $\mathrm{AGB} = 57.41\ \ln \mathrm{NDMI}$	0.549	18.5	5.62	0.034

AGB in Mg/ha; B are spectral bands of Landsat 7 ETM+.

The NDVI performed better than the NDMI for establishing a regression model to estimate above-ground biomass (Table 3). The NDMI is known to be a better indicator of this variable in dense humid forests than in dry forests (Freitas et al., 2005).

The multi-temporal analysis indicated a stronger correlation between remote sensing data and above-ground biomass for the early dry season (fall) than for summer and winter. These results may be due to a differential phenological response of the vegetation types (trees, shrubs and grasses) to varying climatic conditions, which is particularly important in relating spectral information to tree cover. Despite the lack of studies on tree phenology for the Chaco region, there is consensus that tree phenology is mainly regulated by endogenous factors (water storage mechanisms) and access to groundwater reserves (Borchert, 1994; Do et al., 2005; Williams et al., 1997). As an example, tree roots in the Chaco forest were reported to 16 m deep (De Gasperi, 1959). Trees react rapidly to the first rains at the beginning of the rainy season through a highly synchronous flush of new leaves. In turn, they show a delay in leaf fall after the beginning of the dry season caused not only by rainfall deficiency but also by a more complex mechanism related to evaporative demand and groundwater availability. In contrast, vegetation that acquire water from the upper soil layer (shrubs and grasses) shows a rapid response to rainfall deficiency at the beginning of the dry season, reflected in a decrease in the photosynthetic activity (Do et al., 2005; Spessa et al., 2005; William and Running, 2004). These mechanisms operating in the phenological cycles of other dry forests may also play a role in the dry Chaco forest. On this basis, trees in the Chaco forest would begin defoliation late in the dry season (June–August) because of their ability to use groundwater. Additionally, trees reach a peak of defoliation at the end of the dry season (September–November) in response to increased evaporative demand under high temperature conditions. Likewise, shrubs and grasses would be affected by the drought at the beginning of the dry season (April–May) because they only have surface roots (in the first top meter) and, according to Kunst and Bravo (2003), by early frosts in May as a consequence of decreased photosynthetic activity. Therefore, it is reasonable to assume that most of the photosynthetic activity taking place early in the dry season (April–May) is carried out by trees, and that more reliable relationships among remote sensing data, tree cover and biomass can be established during this season.

It is necessary to determine the particular environmental conditions of each year because interannual climatic variation affects the phenology of the forest, thereby altering the spectral response. This hypothesis is supported by rainfall data from the center of the study area (Taco Pozo, Chaco) (Galván et al., 2003; SAGPyA, 2007). In April 2003 (beginning of the dry season) the accumulated rainfall values recorded during 6 weeks before image acquisition (344 mm) exceeded the mean value for that period

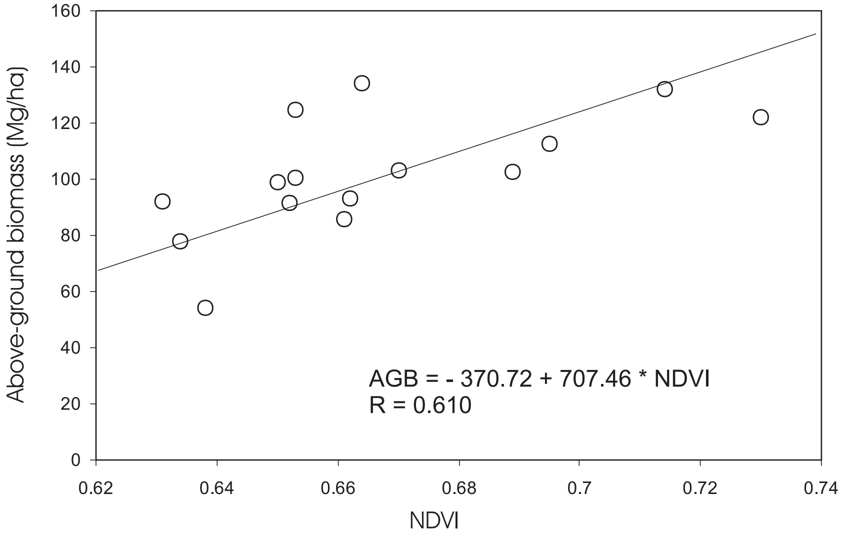

Fig. 4. NDVI linear model fitted by Reduced Major Axis method (RMA) to predict above-ground biomass (AGB) of the dry Chaco forest. Dots represent data used to fit the model.

(145 mm) and were more than half the annual rainfall values (around 650 mm). This might explain the similarities between the forest spectral signature in April 2003 (Fig. 2) and those acquired in summer when rainfall is higher. Thus, the images of April 2003 are unsuitable for biomass estimation because of the lack of significant correlations (Table 2), which resulted from a change in the rainfall regime. On the other hand, the images of May 2002 correspond to a period of normal rainfall.

It is important to point out that the RMA approach applied an internal evaluation that used jackknife and bootstrapping methods to guarantee the consistency of the model, but an independent evaluation assessment of the map was not performed. Nevertheless, this map constitutes a very useful product for the analysis of the distribution of biomass patterns. There is a regional pattern of decreasing above-ground biomass with decreasing rainfall in the east-west direction (Fig. 5b). Local patterns of biomass distribution,

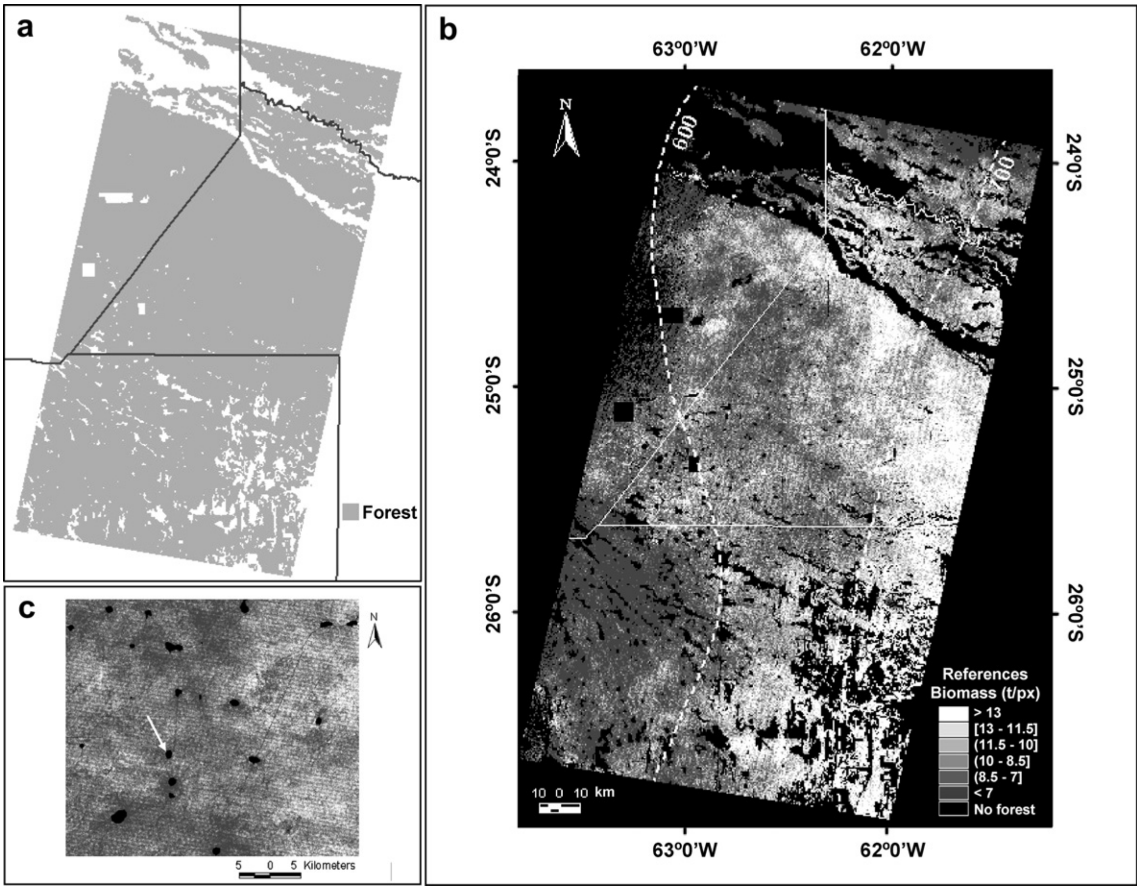

Fig. 5. Forest biomass map in the Semiarid Chaco subregion of Argentina: (a) forest extent, (b) regional pattern; and (c) local pattern (the arrow indicates as an example one of the “puestos”). px: Pixel; 1 t/ha = 1 Mg/ha = 9 Mg/px; solid line: province boundaries; stripped white line: isohyets (mm/year).

probably related to land-use factors, can also be observed (Fig. 5c). Low biomass forests are found near those sites dedicated to cattle ranch ("puestos"). Each "puesto" has some precarious buildings, farmyards and a water source for the animals. Between 100 and 500 cattle heads use the forest for as far as 5 km from the "puesto" for feeding purposes, but they come back to the water source. This can be observed in the map as a concentric degradation pattern with the "puesto" at the center (Fig. 5c). In areas with strong degradation due to overgrazing, important extensions of bare soil can be found. For more information about the "puestos" system and its impact on the forest see Grau et al. (2008). Also, low biomass forests can be found near roads where wood is being extracted continuously due to easy access to these areas.

The results obtained support the use of the methodological approach presented in this study. We consider that there are many ways to improve biomass estimation and landscape pattern identification. First, an increase in the number of field samples will enable us to obtain better adjusted equations to estimate above-ground biomass and to validate data. To develop a method for monitoring forest biomass, independent samples are essential to evaluate the model and the uncertainties. Moreover, different remote sensing data sources may help to improve AGB estimation. For example, high-resolution satellite images from IKONOS or current aerial photographs might replace part of field data (Souza et al., 2003), radar data can be used as a complement since microwave backscatter is sensitive to vegetation structural properties (Ferrazoli and Guerriero, 1995; Saatchi et al., 2000), and hyperspectral data provide information on tree species composition (Asner et al., 2005).

Our results indicate that the degree of accuracy of the relationship remote sensing data-biomass depends on the date of image acquisition. Therefore, images with a higher temporal resolution offer great potential for biomass mapping. In this sense, the use of TERRA/MODIS satellite data (16-day composites of vegetation indexes and spatial resolution of 250 m or 500 m) is an option to be explored. Despite the lower spatial resolution of these images, the estimation of AGB may not be substantially limited because the Chaco region shows a continuum of forests over large areas (more than 1 million ha). Furthermore, the images would be particularly useful for identifying regional spatial patterns because they cover extended areas (Braswell et al., 2003; Huete et al., 2002).

5. Conclusions

Information on forest structure and particularly on biomass at a regional level is relevant for global change research. In this context, remote sensing provides valuable data that can be related to field measurements for the development of environmental monitoring techniques. Our results suggest that above-ground biomass in the dry Chaco forest can be estimated from Landsat 7 ETM+ data with a NDVI linear equation.

The differential vegetation phenology, which is strongly associated with ground water availability, emerged as critical in determining the better image acquisition date to evaluate relationships between forest structure and spectral data. The use of remote sensing data at the beginning of the dry season led to accurate above-ground biomass estimates since grasses and shrubs suffer more intensely from water shortage than trees.

Although the NDVI has been widely used in describing the relationship between vegetation characteristics and spectral data, results vary depending on the ecosystem under study. In this work, NDVI appears as a good indicator of biomass mainly because it does not saturate in sparse forests and is more sensitive to canopy parameters related to absorption of photosynthetically active radiation.

This work not only contributes to the assessment of the status of Chaco ecosystems, but also provides methodological approaches to be considered in future studies in other dry woody ecosystems as Monte region in Argentina or other sectors of Chaco region in Bolivia and Paraguay; and to make comparisons among analogous dry forest ecosystems at global scale. Additionally, accurate methods for monitoring biomass and carbon stocks are necessary to be part of international initiatives to sustainable development, forest conservation and climate change (e.g., Reducing Emissions from Deforestation and Forest Degradation, REDD) and this work represents a valuable contribution in this direction for the Chaco region.

Until today, estimates of dry Chaco forest biomass were available only for some specific sites (Bonino, 2006). Therefore, our results offer a great potential for increasing the understanding of forest structure and biomass distribution at a regional scale. This information is necessary for obtaining more reliable carbon estimates and for better planning, management and conservation of these ecosystems. In Argentina, only 1.4% of the Semiarid Chaco subregion is protected (Brown and Pacheco, 2006) and the methodological approach proposed here can help to identify potential conservation and restoration areas, when subjected to heavy anthropogenic pressure.

Acknowledgements

We are grateful to H.R. Grau, L. Paolini and F. Grings for their valuable comments on the manuscript and to the staff of the Forest Division (Dirección de Bosques) for their collaboration, in particular M. Burghi for providing data of wood density. This work is a part of N.I. Gasparri's Ph.D. thesis supported by a scholarship from CONICET, Argentina. Landsat images were provided by CONAE (Comisión Nacional de Actividades Espaciales).

We also want to specially thank comments and suggestions of anonymous reviewers.

References

Achard, F., Eva, H.D., Mayaux, P., Stibig, H.J., Beldward, A., 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles 18, GB2008. doi:10.1029/2003GB002142.

Arroyo-Mora, J.P., Sánchez-Azofeifa, G.A., Kalacska, M.E.R., Rivard, B., 2005. Secondary forest detection in a neotropical dry forest landscape using Landsat 7 ETM+ and IKONOS imagery. Biotropica 37, 497–507.

Asner, G.P., 1998. Biophysical and biochemical sources of variability in canopy reflectance. Remote Sensing of Environment 64, 234–253.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N., 2005. Selective logging in the Brazilian Amazon. Science 310, 480–482.

Bohonak, A.J., 2004. RMA Software for Reduced Major Axis Regression. San Diego University. http://www.bio.sdsu.edu/pub/andy/rma.html.

Boletta, P.E., Ravelo, A.C., Planchuelo, A.M., Grillo, M., 2006. Assessing deforestation in the Argentine Chaco. Forest Ecology and Management 228, 108–114.

Bonino, E.E., 2006. Changes in carbon pools associated with a land-use gradient in the Dry Chaco, Argentina. Forest Ecology and Management 223, 183–196.

Borchert, R., 1994. Soil and stem water storage determine phenology and distribution of tropical dry forest trees. Ecology 75, 1437–1449.

Braswell, B.H., Hagen, S.C., Frolking, S.E., Salas, W.A., 2003. A multivariable approach for mapping sub-pixel land cover distributions using MISR and MODIS: application in the Brazilian Amazon region. Remote Sensing of Environment 87, 243–256.

Brown, A.D., Pacheco, S., 2006. Propuesta de actualización del mapa ecorregional de la Argentina. In: Brown, A.D., Martínez Ortiz, U., Acerbi, M., Corcuera, J. (Eds.), Situación Ambiental Argentina 2005. FVS-WWF, Buenos Aires, pp. 28–30.

Brown, S., 1997. Estimating Biomass and Biomass Change of Tropical Forests: a Primer. FAO Forestry Paper N° 134. FAO.

Cabrera, A.L., 1976. Regiones Fitogeográficas de Argentina. ACME, Buenos Aires.

Cohen, W.B., Maiersperger, T.K., Gower, S.T., Turner, D.P., 2003. An improved strategy for regression of biophysical variables and Landsat ETM+ data. Remote Sensing of Environment 84, 561–571.

Costa, T.C.C., Oliveira Accioly, L.J., Oliveira, M.A.J., Burgos, N., Silva, F.H.B.B., 2002. Phytomass mapping of the "Seridó Caatinga" vegetation by the plant area and the normalized indices. Scientia Agricola 59, 707–715.

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D., Townshend, J., 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations of the 1980s and 1990s. Proceedings of the National Academy of Sciences 99, 14256–14261.

De Gasperi, L.J.B., 1959. Los trabajos de recuperación bioambiental de la estación biológica de Ingeniero Juárez (Formosa). Revista de Agronomía del Noroeste Argentino 3, 177–199.

Dinerstein, E., Olson, D.M., Graham, D.J., Webster, A.L., 1995. A Conservation Assessment of the Terrestrial Ecoregions of Latin America and the Caribbean. WWF and World Bank, Washington DC.

Do, F.C., Goudiaby, V.A., Gimenez, O., Diagne, A.L., Diouf, M., Rocheteau, A., Akpo, L. E., 2005. Environmental influence on canopy phenology in the dry tropics. Forest Ecology and Management 215, 319–328.

Dong, J., Kaufmann, R.K., Myneni, R.B., Tucker, C.J., Kauppi, P.E., Liskid, J., Buermann, W., Alexeyev, V., Hughes, M.K., 2003. Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources, and links. Remote Sensing of Environment 84, 393–410.

Dymond, C.C., Mladenoff, D.J., Radeloff, V.C., 2002. Phenological differences in Tasseled Cap indices improve deciduous forest classification. Remote Sensing of Environment 80, 460–472.

Eva, H.D., Belward, A.S., De Miranda, E.E., Di Bella, C.M., Gond, V., Huber, O., Jones, S., Sgrenzaroli, M., Fritz, S., 2004. A land cover map of South America. Global Change Biology 10, 731–744.

Fearnside, P.M., 1997. Greenhouse gases from emission form deforestation in Brazilian Amazonia: net committed emissions. Climatic Change 35, 321–360.

Fearnside, P.M., 2000. Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46, 115–158.

Feeley, K.J., Gillespie, T.W., Terborgh, J.W., 2005. The utility of spectral indices from Landsat ETM+ for measuring the structure and composition of tropical dry forest. Biotropica 37, 508–519.

Ferrazoli, P., Guerriero, L., 1995. Radar sensitivity to tree geometry and woody volume: a model analysis. IEEE Transactions on Geosience and Remote Sensing 33, 360–371.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J.A., Ramankutty, N., Snyder, P., 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Frontiers in Ecology and the Environment 5, 25–32.

Foody, G.M., Boyd, D.S., Cutler, M.E.J., 2003. Predictive relations of tropical biomass from Landsat TM data and their transferability between regions. Remote Sensing of Environment 85, 463–474.

Freitas, S.R., Mello, M.C.S., Cruz, C.B.M., 2005. Relationships between forest structure and vegetation indices in Atlantic Rainforest. Forest Ecology and Management 218, 353–362.

Galván, L., Infante, C., Acuña, L.R., Angueira, C., 2003. Análisis espacial de precipitaciones en la provincia de Santiago del Estero a escalas temporales mensual y anual. In: Proceedings Congreso Regional de Ciencia y Tecnología NOA. Secretaría de Ciencia y Tecnología, Universidad Nacional de Catamarca.

Gasparri, N.I., Grau, H.R., Manghi, E., 2008. Carbon pools and emissions from deforestation in extra-tropical forest of northern Argentina between 1900 and 2005. Ecosystems 11, 1247–1261.

Gasparri, N.I., Grau, H.R., 2006. Patrones regionales de deforestación en el subtrópico argentino y su contexto ecológico y socioeconómico. In: Brown, A.D., Martínez Ortiz, U., Acerbi, M., Corcuera, J. (Eds.), Situación Ambiental Argentina 2005. FVS-WWF, Buenos Aires, pp. 442–446.

Gilabert, M.A., González-Piqueras, J., García-Haro, J., 1997. Acerca de los índices de vegetación. Revista de teledetección 8, 1–10.

Gillespie, T.W., 2005. Predicting woody-plant species richness in tropical dry forests: a case study from South Florida, USA. Ecological Application 15, 1.

Giménez, A.M., Moglia, J.G., 2003. Árboles del Chaco Argentino: guía para el reconocimiento dendrológico. UNSE-SAyDS, Santiago del Estero, Argentina.

Grau, H.R., Aide, T.M., Gasparri, N.I., 2005a. Globalization and soybean expansion into semiarid ecosystems of Argentina. Ambio 34, 265–266.

Grau, H.R., Gasparri, N.I., Aide, T.M., 2005b. Deforestation trends and soybean expansion in subtropical Argentina. Environmental Conservation 32, 140–148.

Grau, H.R., Gasparri, N.I., Aide, T.M., 2008. Balancing food production and nature conservation in the neotropical dry forests of northern Argentina. Global Change Biology 14, 985–997.

Hoekstra, J.M., Boucher, T.M., Ricketts, T.H., Roberts, C., 2005. Confronting a biome crisis: global disparities of habitat loss and protection. Ecology Letters 8, 23–29.

Hougthon, R.A., 2005. Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945–958.

Hueck, K., 1978. Los bosques de Sudamérica. Ecología, composición e importancia económica. GTZ, Eschborn, BRD.

Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). Remote Sensing of Environment 25, 295–309.

Huete, A., Didan, K., Miura, T., Rodríguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83, 195–213.

INTI-CITEMA (Instituto Nacional de Tecnología Industrial-Centro de Investigaciones Tecnológicas de la Madera), 2008. Listado de densidades de maderas. http://www.inti.gov.ar/maderas/pdf/densidad_cientifico.pdf.

Kalacska, M.E.R., Sánchez-Azofeifa, G.A., Caelli, T., Rivard, B., Boerlage, B., 2005. Estimating leaf area index from satellite imagery using Bayesian networks. IEEE Transactions on Geosience and Remote Sensing 43, 1866–1873.

Kaufman, Y.J., 1989. The atmospheric effect on remote sensing and its correction. In: Asrar, G. (Ed.), Theory and Application of Optical Remote Sensing. Wiley Publication, New York.

Klinck, C.A., Machado, R.B., 2005. Conservation of the Brazilian Cerrado. Conservation Biology 19, 703–713.

Kunst, C.R., Bravo, S., 2003. Ecología y régimen de fuego en la región chaqueña argentina. In: Kunst, C.R., Bravo, S., Panigatti, J.L. (Eds.), Fuego en los ecosistemas argentinos. INTA, Santiago del Estero, pp. 109–118.

Lawrence, R.L., Ripple, W.J., 1998. Comparisons among vegetation indices and bandwise regression in a highly disturbed, heterogeneous landscape: Mount St. Helens, Washington. Remote Sensing of Environment 64, 91–102.

Lu, D., Mausel, P., Brondízio, E., Moran, E., 2004. Relationships between forest stand parameters and Landsat TM spectral responses in the Brazilian Amazon Basin. Forest Ecology and Management 198, 149–167.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V., Gordon, J.E., 2006. A global overview of the conservation status of tropical dry forests. Journal of Biogeography 33, 491–505.

Minetti, J.L., 1999. Atlas Climático del Noroeste Argentino. Laboratorio Climatológico Sudamericano, Fundación Zon Caldenius, Tucumán, Argentina.

Nepstad, D.C., Verissimo, A., Alencart, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cocrhane, M., Brooks, V., 2003. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398, 505–5008.

Purevdorj, T., Tateishi, R.T.I., Honda, Y., 1998. Relationships between percent vegetation cover and vegetation indices. International Journal of Remote Sensing 19, 3519–3535.

SAGPyA (Secretaría de Agricultura Ganadería Pesca y Alimentación), 2007. Registro pluviométricos semanales 1999–2004 (Chaco-Alte. Brown, Taco Pozo). http://www.sagpya.mecon.gov.ar/.

SAyDS (Secretaría de Ambiente y Desarrollo Sustentable), 2005. Primer Inventario Nacional de Bosques Nativos. (First National Native Forest Inventory of Argentina). Manual de Campo. Proyecto Bosques Nativos y Áreas Protegidas, Préstamo BIRF 4085 – AR (1998-2005). SAyDS, Buenos Aires, Argentina.

SAyDS (Secretaría de Ambiente y Desarrollo Sustentable), 2007. Primer Inventario Nacional de Bosques Nativos. (First National Native Forest Inventory of Argentina). Informe Regional Parque Chaqueño. Proyecto Bosques Nativos y Áreas Protegidas, Préstamo BIRF 4085 – AR (1998-2005). SAyDS, Buenos Aires, Argentina.

Saatchi, S.S., Nelson, B., Podest, E., Holt, J., 2000. Mapping land cover types in the Amazon Basin using 1 km JERS-1 mosaic. International Journal of Remote Sensing 21, 1201–1234.

Sánchez-Azofeifa, G.A., Quesada, M., Rodríguez, J.P., Nassar, J.M., Stoner, K.E., Castillo, A., Garvin, T., Zent, E.L., Calvo-Alvarado, J.C., Kalacska, M.E.R., Fajardo, L., Gamon, J.A., Cuevas-Reyes, P., 2005. Research priorities for neotropical dry forests. Biotropica 37, 477–485.

Sevola, Y., 1975. Cubicación de árboles en el inventario forestal del noroeste argentino. Doc. de trabajo N° 20. FAO: DP/ARG/70/536. Salta, Argentina.

Souza Jr., C., Firestone, L., Moreira Silva, L., Roberts, D., 2003. Mapping forest degradation in the Eastern Amazon from SPOT 4 through spectral mixture models. Remote Sensing of Environment 87, 494–506.

Spessa, A., McBeth, B., Prentice, C., 2005. Relationship among fire frequency, rainfall and vegetation patterns in the wet-dry tropics of northern Australia: an analysis based on NOAA-AVHRR data. Global Ecology and Biogeography 14, 439–454.

Steininger, M.K., 2000. Satellite estimation of tropical secondary forest aboveground biomass: data from Brazil and Bolivia. International Journal of Remote Sensing 21, 1139–1157.

Steininger, M.K., Tucker, C.J., Erts, P., Killeen, T.J., Villegas, Z., Hecht, S.B., 2001. Clearance and fragmentation of tropical deciduos forest in the Tierras Bajas, Santa Cruz, Bolivia. Conservation Biology 15, 856–866.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8, 127–150.

UMSEF (Unidad de Manejo del Sistema de Evaluación Forestal), 2007. Monitoreo de la superficie de bosque nativo de Argentina. www.ambiente.gov.ar/umsef.

Vitusek, P.M., 1994. Beyond global warming: ecology and global change. Ecology 75, 1861–1876.

William, M.J., Running, S.W., 2004. Effect of precipitation and soil water potential on drought deciduous phenology in the Kalahari. Global Change Biology 10, 303–308.

Williams, R.J., Myers, B.A., Muller, W.J., Duff, G.A., Eamus, D., 1997. Leaf phenology of woody species in a north Australian tropical savanna. Ecology 78, 2542–2558.

Wilson, E.H., Sader, S.A., 2002. Detection of forest harvest type using multiple dates of Landsat TM imagery. Remote Sensing of Environment 80, 385–396.

World Wildlife Fund (WWF), 2001. Central American Dry Forests (NT0209). http://www.worldwildlife.org/wildworld/profiles/terrestrial/nt/nt0209_full.html.

Zak, M.R., Cabido, M., Hodgson, J.G., 2004. Do subtropical seasonal forests in the Gran Chaco, Argentina, have a future? Biological Conservation 120, 589–598.

Zar, J.H., 1999. Biostatistical Analysis. Prentice Hall.