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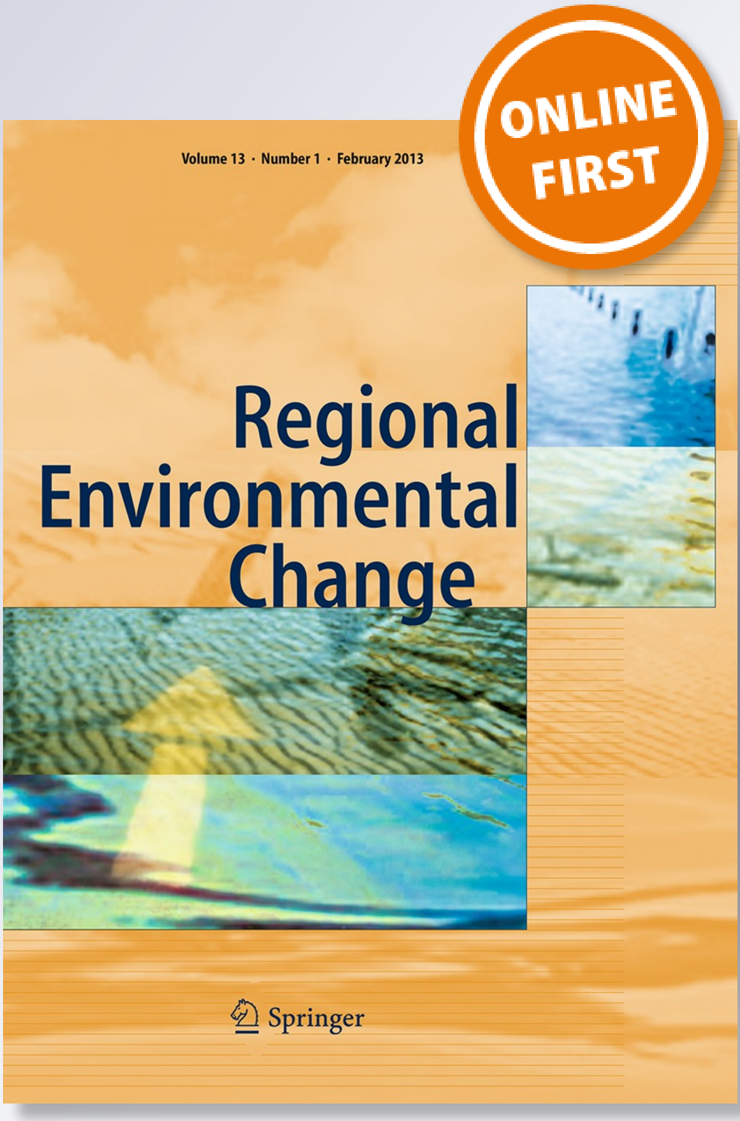

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ORIGINAL ARTICLE

Regional patterns and controls of biomass in semiarid woodlands: lessons from the Northern Argentina Dry Chaco

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Abstract Land use change, particularly in forested ecosystems, has a direct impact on the global carbon cycle. Consequently, the regional assessment of biomass and the understanding of its current spatial controls are research priorities for regional ecology and land use. Field data and satellite imagery were combined here to map woodlands and estimate their above-ground biomass (AGB) in the Dry Chaco ecoregion of northern Argentina. Allometric equations were used to derive AGB from diameter at breast height data collected at 50 samples during 2007. In order to generate the AGB regional map, this information was later associated with MODIS-Terra spectral data (NDVI) using the Random Forest (RF) method. Finally, AGB spatial patterns were associated with potential biophysical and human controlling factors through correlation and regression analyses. Results indicate that the use of RF and NDVI of the dry season derived from MODIS-Terra was suitable to map regional AGB, what makes this methodology applicable to other dry woodlands. The RF model used to map AGB showed a mean deviation of 2.9 % and a precision of 15 % for one prediction. At this regional scale of analysis, biophysical rather than human factors controlled AGB spatial patterns, in part because the region includes a wide range of environmental situations. Warmer conditions showed a higher biomass, suggesting an energetic limitation for AGB accumulation. However, human controls (distance to towns, cultivation, and roads) also conditioned AGB patterns, suggesting lower AGB values near cultivated areas. The relation between AGB and water availability was surprisingly weak, but partially obscured by the land use history and degradation due to extensive cattle ranching. We propose that a combination of environmental factor and land use affects the AGB regional patterns and promotes unexpected relationships with environmental factors. This work represents the first spatially explicit AGB (patterns and controls) analysis for an extensive subtropical dry woodland area (113,000 km^2) and shows how biophysical and human factors co-control regional patterns.

Keywords Subtropical dry woodlands · Above-ground biomass · Forest degradation · Land use · Random Forest · Remote sensing

Introduction

Beyond the general agreement that biomass stock could be used as a variable of forest degradation (Asner et al. 2008), our understanding of its spatial regional patterns in relation to context factors (i.e., biophysical and human traits) remains limited to small-extent areas (Dahlin et al. 2012; Asner et al. 2008). In this sense, the generation of biomass maps and their linkage to spatially explicit context data represent an opportunity to understand which mechanisms control this fundamental ecosystem characteristic. This methodological approach was used recently in dry woodlands

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of North America (Huang et al. 2009; Dahlin et al. 2012) and tropical forest of Hawaii (Asner et al. 2008), and Madagascar (Asner et al. 2012). Recently, biomass mapping attempts have been made at global (Saatchi et al. 2011) and at regional scales, for the Amazon basin (Saatchi et al. 2007), Russia (Houghton et al. 2007), North America (Blackard et al. 2008), China (Zheng et al. 2007), and Africa (Baccini et al. 2008). All these characterizations were based on satellite data and used nonparametric regression techniques, as Random Forest (a machine learning method that adjusts an ensemble of regression trees by re-sampling; Breiman 2001).

Forest degradation is a human-induced change responsible for important structural and functional alterations of ecosystems. Common drivers of this degradation are anthropogenic fires, extensive cattle ranching, logging, and firewood production. Degradation involves decreasing tree cover, biomass, and species richness, as well as modifications in soil protection, water cycle regulation, carbon store and fixation, or habitat for biodiversity conservation (IPCC 2003). The evidence about the importance of deforestation and forest degradation in the global carbon balance promoted the inclusion of the carbon emission reduction from forests (i.e., REDD+) into a climate change agreement (UN-Redd 2012) and generated a new international policy context, where management and degradation are relevant aspects to be monitored and evaluated (Houghton 2005).

Dry lands encompass 6 % of the world forested area (Malagnoux et al. 2007) and currently face high rates of transformations by replacement (with croplands and pastures) and woody vegetation structure degradation (le Polain de Waroux and Lambin 2012). These changes occur under highly contrasting human contexts, as different subtropical dry forest areas show variable human population densities (from 1 to 465 inh km^{-2}) and rural economies that range from subsistence to large-scale (industrial) commodity production (Baldi and Jobbágy 2012). In South America, the Dry Chaco (northern Argentina; southeast of Bolivia and West of Paraguay) preserves the second largest forested ecosystem of the continent after the Amazon, with the largest and less-fragmented cover within the Neotropic dry woodlands (including dry shrubs, savannas, and forests) (Portillo-Quintero and Sánchez-Azofeifa 2010). Simultaneously, the region faces accelerated deforestation (Clark et al. 2010) and carbon emission processes (Gasparri et al. 2008). Despite these conditions, at present, there are no available regional characterizations of biomass patterns and controls urgently needed to evaluate potential impacts of land use and climate change. Preliminary analyses have demonstrated the feasibility of regional biomass mapping through the combination of field and remotely sensed data in the Dry Chaco (Gasparri et al. 2010). Indeed, these analyses suggested that in the dry season, trees contribute with most of green leaf area, as understory vegetation drastically reduces its green leaf area due to water scarcity and frost. Despite Dry Chaco is an extensive region under contrasting land use process (Grau et al. 2008) with significant impacts for the regional carbon balance (Gasparri et al. 2008), at present there are no available regional studies to explore the main controls over the biomass in the region.

The objectives of this study were to (a) prepare an above-ground biomass map for woodlands in the Dry Chaco ecoregion, (b) explore at a regional scale the biophysical and human factors that could affect biomass accumulation, and (c) discuss the implications of our results in the process of assessing and monitoring vegetation degradation and carbon balance in dry woodlands.

Methods

In this work, we first characterized regional land cover in order to identify woodland areas. We then estimated regional woodlands above-ground biomass (AGB) from field data and MODIS satellite imagery. Finally, we explored the biophysical and human drivers of regional AGB patterns by means of correlation and regression analyses, using climatic and base cartography.

Study region

The Dry Chaco covers ca. 1.2 million km^2 (Dinerstein et al. 1995) in northern Argentina, southeastern Bolivia, and western Paraguay (Fig. 1). A sub-humid monsoonal rainfall pattern (400 to 1,500 mm year^{-1}) and occasional extreme temperatures (up to 48 °C) (Prado 1993) determine a marked water deficit, especially during the southern hemisphere springtime (from September to December). Under these conditions, vegetation is dominated by broadleaf, deciduous, or semi-deciduous trees, being this vegetation frequently considered a neotropical dry forest (Gentry 1995; Eva et al. 2004). However, two aspects make vegetation in this region a peculiar dry forest: in terms of its floristic composition, it is a subtropical extension of a temperate formation (Pennington et al. 2000), and in terms of its climate, it is regularly frost in winter (from May to August).

As a consequence of a combination of environmental gradients and a varied history of land use and disturbance rates, woody vegetation in the Argentinean portion of the Dry Chaco shows a high variability in structural and functional terms (Tálamo and Caziani 2003; Bonino and Araujo 2005; Bonino 2006). Records about tree basal area range from 1 to 15 m^2 ha^{-1}, according to the First National Native Forest Inventory of Argentina (SAyDS 2007) and

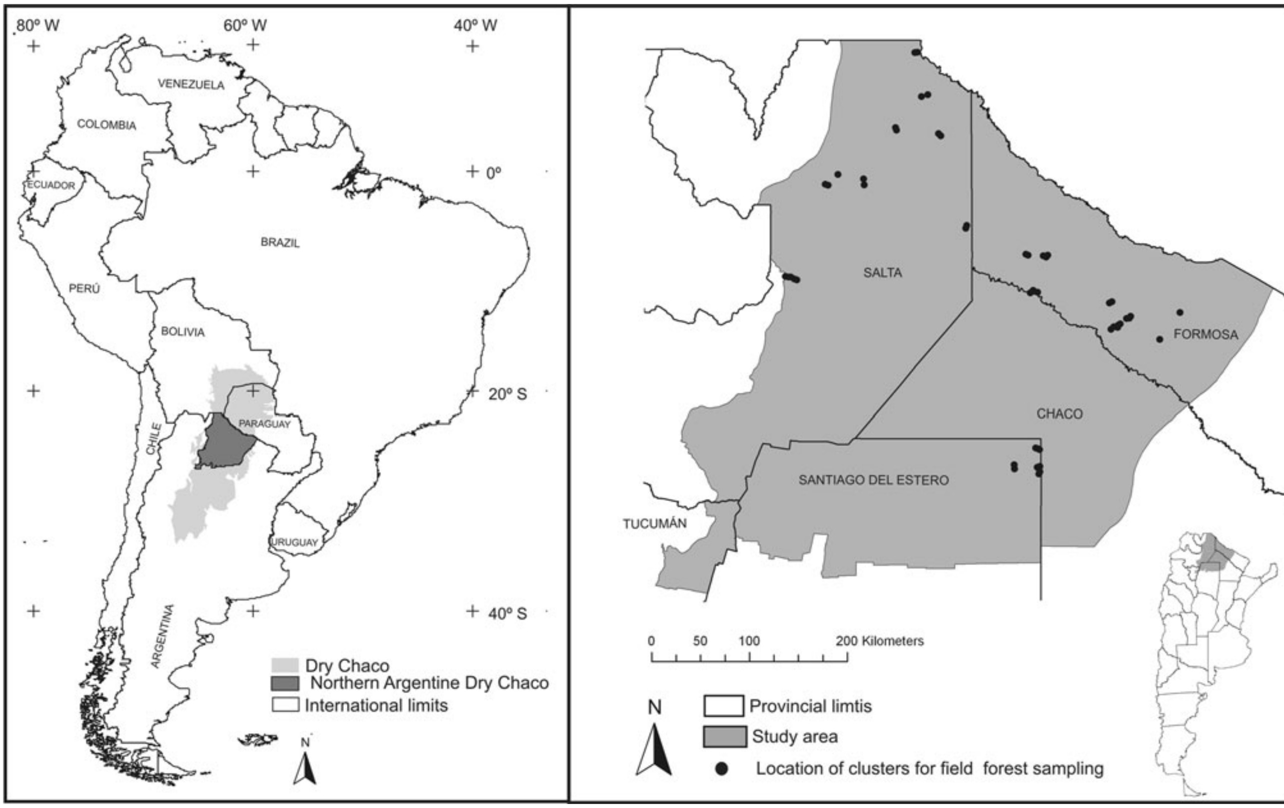

Fig. 1 Study area and regional distribution of the 50 clusters used to estimate the forest AGB

for AGB from 54 to 135 Mg ha^{-1} (Gasparri et al. 2010). The factors usually identified as drivers of this variability are selective logging, extensive cattle ranching, firewood and charcoal extraction, and occasional anthropic fires. Selective logging is frequently conditioned by the road network and the distance to towns and cities (Ahrends et al. 2010). Extensive cattle ranching, and firewood and charcoal extraction are articulated around inhabited sites with basic infrastructure locally known as "puestos." The effects of the "puestos" system over the vegetation structure was early described by Morello and Saravia–Toledo (1959) and more recently at local scale by Macci and Grau (2012) and at regional scale by Grau et al. (2008). Additionally, even though the region preserves an almost continuous cover of natural vegetation, it faces a deforestation process driven by modern agriculture since the 1990s, which was well documented for sectors of Argentina (e.g., Zak et al. 2004; Boletta et al. 2006; Gasparri and Grau 2009), but generalized in the whole region (Clark et al. 2010).

In particular, the biomass depletion process starts with the selective logging of high (12–20 m) and economically valuable trees, including semi-deciduous (i.e., *Bulnesia sarmientoi*, *Prosopis alba*, *Schinopsis lorentzeii*) and perennial species (*Aspidosperma quebracho-blanco*). A second step results from logging for domestic uses (e.g., charcoal and firewood production) oriented to deciduous small trees (6–10 m tall) and less valuable species (i.e., *Zizipus mistol, Caesalpinea paraguarensis, Prosopis nigra*). Domestic logging is commonly coupled with cattle ranching around "puestos," leading surrounding vegetation to an ultimate phase of depletion of the shrub layer. Along this gradient, a progressive domination of deciduous small trees and shrubs become evident (*Prosopis spp.*, *Acacia spp.*, *Ruprechtia triflora*, *Celtis spp.*). In resume, we suggest that the progressive woody biomass depletion in the region represents the reduction of the tree cover with a change of dominance from perennial and semi-deciduous tall trees to deciduous low trees and shrubs. The National Forest Inventory of Argentina defines forest as any area with tree cover above 20 % (UMSEF 2012). This represents a wide range of woody vegetation situations, from a dominance of large trees to a one of remnant understory shrubs. In this paper, we decided to use the term woodlands to make reference to this mosaic of patches of vegetation under diverse tree cover degrees (by biophysical and/or human causes), but it is equivalent to forest definition of the National Forest Inventory.

Our study area is located in the northern portion of the Argentinean Dry Chaco (between 22–27°S and 59.5–65°W), encompassing parts of the provinces of Tucumán, Santiago del Estero, Chaco, Salta, and Formosa

(Fig. 1). It covers 176,000 km^2 and includes a significant fraction of the largest continuum of woodlands in Argentina, locally called "El Impenetrable." The area is characterized by a flat relief and soils formed by aeolian and fluvial sediments coming from the main rivers (Pilcomayo, Bermejo, and Salado). Mean annual temperature ranges from 19 to 24 °C; average coldest (July) and hottest (January) months temperature are 16 and 28 °C, respectively. Annual rainfall is low (between 400 and 900 mm year^{-1}), with a strong pattern of monsoonal seasonality occurring mainly between November and March (Minetti 1999). West and East borders correspond to the rainy areas (900 mm year^{-1}), while the central sector to dry ones (400 mm year^{-1}). The main economic activities within the study area are cattle ranching and charcoal production around "puestos," and soybean cultivation in areas with >700–800 mm year^{-1} of rainfall (Grau et al. 2005; Gasparri and Grau 2009).

MODIS imagery and land cover mapping

The MODIS product MOD13Q1 (Collection 5) was used in the land cover and AGB mapping processes. This product, has a spatial resolution of 250 m, includes the enhanced vegetation index (EVI) and the normalized difference vegetation index (NDVI), as well as blue, red, near infrared, and mid-infrared bands, with a 16-day compositing scheme that helps eliminate cloudy and other unreliable pixels. The entire study area was encompassed within the h11v12 tile.

Mapping land cover allowed us to frame our study to exclusively the woodland cover, in order to later design AGB field sampling and explore AGB patterns and their relationships with biophysical and human factors. Previous to the land cover digital classification, cultivated areas were excluded by a visual interpretation of nine Landsat TM images of year 2007 from the catalog of the Instituto Nacional de Pesquisas Espaciais (INPE 2012). These areas are characterized by their regular shape, the presence of plow or crop lines and have nearby infrastructure (Clark et al. 2010). This method was the standard procedure of the forest monitoring system of Argentina (UMSEF 2012) and was previously used in the region to describe deforestation (Grau et al. 2005; Grau et al. 2008; Gasparri and Grau 2009). For the non-cultivated areas, a supervised classification was performed using the four spectral bands of MOD13Q1 from the end of the wet season (starting date 3/6/07), the cold dry winter (starting date 7/12/07), and the warm dry spring season (starting date 10/16/07). These three periods capture key phenological situations in the region.

The classification was based on the nonparametric Random Forest (RF) algorithm (Breiman 2001; Gislason et al. 2006), which is based on the re-sampling (bagging) of training sites to form an ensemble of classification trees. RF includes an internal evaluation based in the re-sampling "Out Of Bag" (OOB) method. In section "AGB estimates from field data and AGB mapping", we explain with more detail the RF method in a regression mode to map AGB. In this work, the following land cover categories were defined: (a) woodlands (any place with three cover above 20 %), (b) permanent water bodies, (c) flooded and riparian vegetation, and (d) grasslands and bare soil (any place with tree cover below 20 %). The selection of training points was made on the basis of field experience over the same Landsat TM images previously described. A total of 600 training points were used: 150 points were used to training the classification (76 of woodlands, 13 of permanent water bodies, 30 of flooded and riparian vegetation, and 31 of grasslands and bare soil) and the remaining points (450) to prepare a confusion matrix (Richards and Xiuping 2006) that evaluates the accuracy of the resulting classification.

AGB estimates from field data and AGB mapping

During the winter of 2007, field sampling was conducted in the Dry Chaco to estimate woodlands AGB. A total of 50 samples were distributed within the region (Fig. 1), encompassing a wide range of—a priory based—vegetation conservation conditions: from good ones in aboriginal communal and protected lands to poor ones in private livestock-devoted lands. Each sample consisted in a 100 × 100 m cluster with a set of circular plots placed at each vertex. Plots were divided in two concentric circles; in the minor or inner circle (with an area of 500 m^2 and a radius of 12.6 m), all stems with a diameter at breast height (DBH) > 10 cm were recorded; in the major circle (area of 1,000 m^2 and radius of 17.8 m), only stems with DBH > 20 cm were recorded. The DBH of 10 cm, adopted as a size limit to include trees in the survey, is a traditional forest inventory procedure in Argentina and, for the case of the Dry Chaco, comprehend all the species of the top and mid-layers and the major individuals of the understory with a large number of stumps with DBH between 10 and 20 cm. For all stems sampled, the species was recorded. Data of each cluster were then analyzed to estimate AGB using global allometric equations developed for dry forests (Chave et al. 2005). This method estimates tree biomass based on DBH and wood density and was indicated as the best technique available to estimate biomass from a forest inventory data when regional and species-specific functions are not available (Gibbs et al. 2007). Wood density was obtained from the database generated by INTI–CITEMA (2010), which includes data for over 200 species. For those species of which there were no specific data available, the average wood density of the region was employed.

The RF method for mapping AGB was applied as an alternative to regressions. RF grows an ensemble of regression trees, in where only a fraction of the samples (in our case plots) is employed for each regression tree, whereas the remaining samples are used to verify predictions of that tree (OOB). In turn, within each tree and in each node, a randomly selected sample of the independent variables is tested. At the end of the process, the method has a set of trees that are grown on the basis of re-sampling of observations and variables. Additionally, RF calculates an importance index for each independent variable based on the relative increase of the prediction error when each independent variable is permuted by another to define a node in a tree (Liaw and Wiener 2002).

Forest biomass depends on the number of trees (density), its size (diameter and height), and wood density. Remote sensing does not estimate biomass directly, but provides information related to other characteristics such as crown size, forest occupation (density and basal area), or tree cover, which are ultimately correlated with biomass (Baccini et al. 2004). Based on previous studies (Gasparri et al. 2010), we selected the NDVI bands as independent variables in the AGB modeling process. The use of RF to map AGB includes three steps: (a) NDVI dates selection, (b) model evaluation, and (c) mapping AGB. To choose the most useful NDVI dates, we tested all the NDVI data corresponding to the year 2007 (23 dates) and selected the dates based on the importance index (Breiman 2001) setting the RF to adjust 1,000 trees. To evaluate models, we use the selected NDVI dates to grow a RF using only 34 clusters of the field sampling, while the remaining 16 clusters were used as independent data to the evaluation. RF model fits were evaluated by explaining the percent of variation and standard error (S). Model predictions were assessed comparing predicted-observed data, from: (a) the deference between means calculated with observed and predicted values, which indicates the error of a set of predictions (set of pixels), (b) the average of absolute difference of each pair of observed and predicted values, which permits estimating the precision of a particular prediction (value of a pixel), and (c) the efficiency of the model (analogous to R^2), which allows evaluating the gain in using the model with respect to the average of the dependent variable (Vanclay 1994). Finally, to map AGB, a RF setting to adjust 1,000 trees was fitted with the complete set of 50 clusters and used to predict the AGB of each pixel exclusively in the areas classified as woodlands.

The entire RF processes were performed with the R software (R Development Core Team 2012) using the Random Forest package (Liaw and Wiener 2002). Land cover and AGB mapping were performed in R software using the YaImpute (Crookston and Finley 2008) and SP (R Development Core Team 2012) packages.

Regional patterns of AGB in relation with biophysical and human factors

A database of twelve biophysical and human variables was compiled for the whole study area (Table 1), using, as far as we know, the most updated and accurate available information. Climatic data came from the “Ten Minute Climatology database” (CRU-UEA, New et al. 2002), representing averaged monthly figures for the 1961–1990 period. In the estimation of the annual ratio between precipitation (PPT) and potential evapotranspiration (PET), which would depict a water availability gradient, PET was calculated using the Penman–Monteith algorithm (Allen et al. 2004). Soil information came from the “Atlas de Suelos de la República Argentina” (INTA-SAGyP 1990). To obtain the percentage of silt, clay, and sand, textural classes (e.g., “silty clay”) were transformed to particle size percentage using the soil textural triangle. Three variables accounted for the mean euclidean distance from human infrastructure (main roads, urban areas, and cultivated areas) and two for the density of this infrastructure (length of roads and trails, and number of “puestos”). Data of Roads (paved and unpaved), trails (for vehicles) and urban areas (towns to cities) came from the “Proyecto Mapear” (Mapear 2012), “puestos” location came from previous surveys performed by Grau et al. (2008) and updated for this analysis, while cultivated areas came from land cover map generated here. These last five variables would depict the permeability of the territory to human interventions.

In order to analyze the correlation among biophysical and human controls (i.e., independent variables), and their associations with AGB (i.e., dependent variable), all the data was summarized in 570 contiguous square cells of 10 × 10 min (the spatial resolution of the least detailed information layer, i.e., climate). After averaging control values within each grid cell, a correlative analysis was performed using the Kendall’s τ nonparametric test (Whittaker 1987). Mean ±1.96 standard deviation (SD) AGB values were calculated within each grid cell, which would represent the most, average, and least depleted local conditions. Finally, we performed regression analyses to identify patterns of AGB in relation to each control. We tested three functions (straight line, second order polynomial, and one phase exponential) for the relationships between the twelve independent variables (Table 1) and the three dependent variables (mean −1.96 SD AGB, mean AGB, and mean +1.96 SD AGB). Model selection was carried out through the Akaike’s information criterion (Akaike 1974).

Table 1 List of biophysical and human variables included in the regression and correlation analyses

Variable	Units	Source
Annual precipitation (PPT)	mm	New et al. (2002)
Annual precipitation : potential evapotranspiration (PPT:PET)	(ratio of mm)	New et al. (2002)
Seasonality	Count months PPT:PET <1	New et al. (2002)
Mean annual temperature	°C	New et al. (2002)
Coldest month temperature	°C	New et al. (2002)
Annual ground frost	days years^{-1}	New et al. (2002)
Soil texture	100-sand %	INTA-SAGyP (1990)
Distance to cultivation	km	This study
Distance to urban areas	km	Mapear (2012)
Distance to main roads	km	Mapear (2012)
Length of roads and trails	km	Mapear (2012)
Number of "puestos"	Number	Grau et al. (2008)

Results

Land cover and AGB map

The land cover map obtained (Fig. 2a) showed that in 2007, 84 % (11,300 km^2) of the non-cultivated territory corresponded to woodlands, 8 % (1,100 km^2) to flooded or riparian vegetation, 7 % (9,000 km^2) to grasslands and bare soils, and only 0.2 % (280 km^2) to permanent water bodies. The confusion matrix generated from RF internal re-sampling (OOB) indicated an overall accuracy of 96 %, while the external evaluation indicated a much lower one of 85 %. The classification accuracy for the woodland class was acceptable according to either internal or external evaluations, with a user accuracy of 98 and 80 %, respectively (Supplementary material 1).

AGB values estimated from our measured 50 clusters ranged between 48 and 212 Mg ha^{-1} with an average of 110 Mg ha^{-1}. It is important to note that our sampling approach encompassed a wide range of AGB conditions, and therefore, the average value may not represent the average regional one. The use of RF to map AGB includes three steps: (a) the NDVI dates selection; (b) model evaluation, and (c) mapping AGB. Based on the importance Index, the selected dates were: July 12, 2007, September 14, 2007, and October 16, 2007. The statistics of the model fitting showed a 48.6 % of variation explained and an AGB standard error of 24 Mg ha^{-1}. The predictions evaluation showed a mean predicted versus mean observed deviation of 2.93 % and an average absolute deviation for a single prediction of ±15 %. The model efficiency was 0.612 calculated following Vanclay (1994). Finally, AGB was mapped using a RF of 1,000 trees using NDVI values of the three selected dates and the whole sample (50 samples). Additionally, the predicted-observed plot showed that the model has an acceptable prediction capacity, although with a tendency to underestimate the highest values. Resulting land cover map and AGB map are showed in Fig. 2b with the predicted-observed plot of the RF model.

Regional patterns of AGB in relation with biophysical and human factors

From the correlation matrix (Table 2), in the northern Argentina Dry Chaco, colder temperatures were associated with more stable-humid conditions, which would favor the cultivation presence. The presence of roads, trails, and inhabited areas (from "puestos" to cities) showed a weak to nil spatial association to the biophysical conditions analyzed. Soil texture was independent from the main biophysical and human gradients.

Regional patterns of AGB in relation with biophysical and human factors are showed in Fig. 3. Under this biophysical and human context, current spatial patterns of AGB mean-cell values would depend on both sets of controls at a regional scale, as a positive association with winter temperature (according to the coldest month temperature; $R^2 = 0.22$) and a negative with the distance to cultivation ($R^2 = 0.18$) were found. These links arose also when considering the highest AGB values (mean +1.96 SD) for a grid cell, except for the annual ground frost. Surprisingly, the water availability (measured by the PPT and its relation with PET) showed a weak relationship. The distances to urban areas and main roads; the densities of "puestos," roads, and trails; and the soil texture showed negligible adjustment values ($R^2 \leq 0.09$) and reveal ambiguous relationships with the biomass across the regional gradient (due to a minor adjustment to the straight line model).

Discussion

Differences in vegetation spectral and temporal behaviors allowed us to estimate the above-ground biomass (AGB)

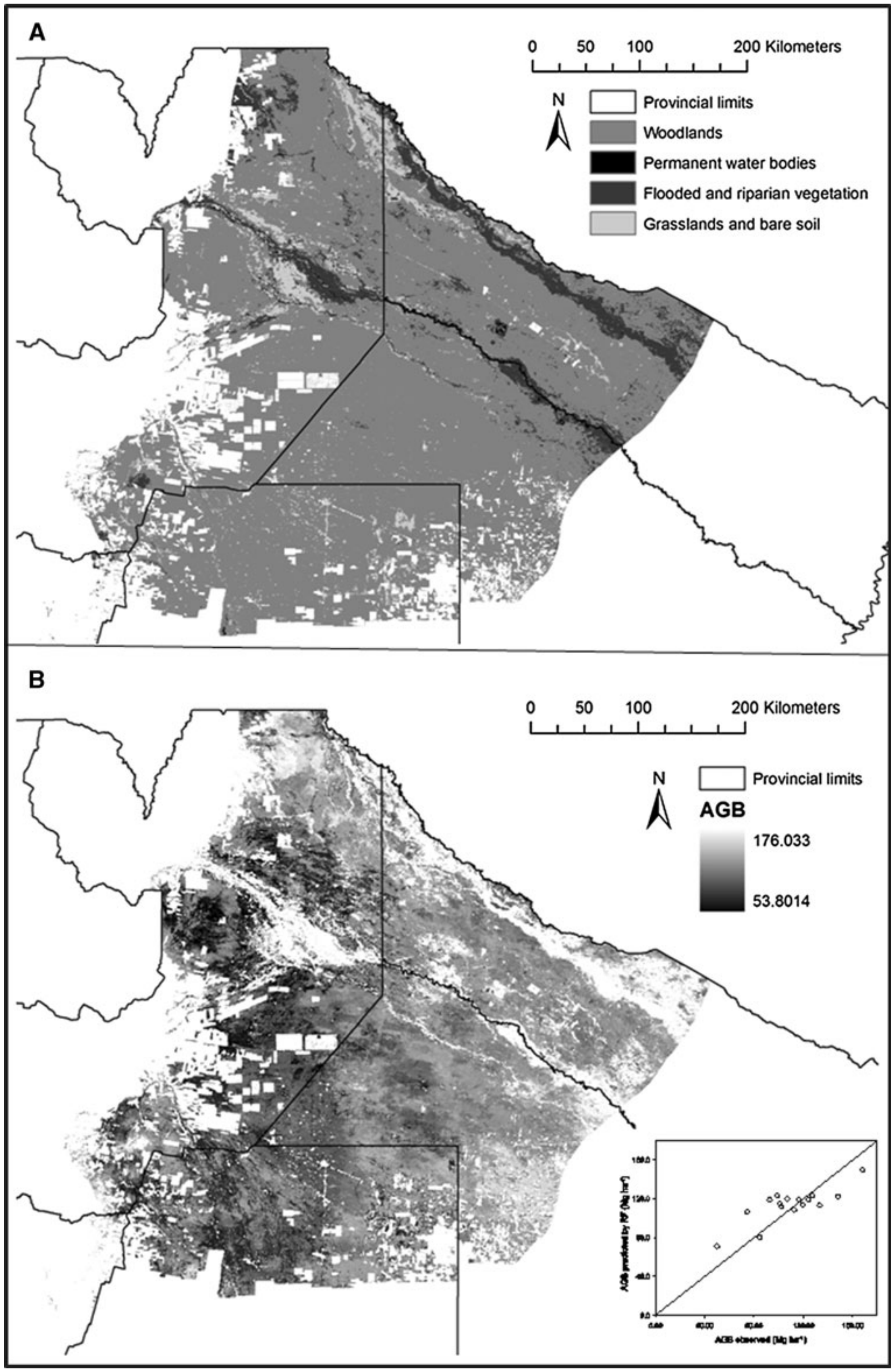

Fig. 2 **a** Land cover map of the study area (2007), excluding cultivated land identified by visual interpretation of Landsat images. Land cover types were mapped with Random Forest classification of MODIS images. **b** AGB (Mg ha^{-1}) map of woodlands in Dry Chaco. AGB was mapped on the basis of a Random Forest model grown with MODIS NDVI data of three dates. Evaluation plot of predicted versus observed is showed in the lower right corner of **b**

patterns in northern Argentina Dry Chaco, one of the neotropical largest and less-fragmented forested ecoregions. In comparison with the only previous regional estimation (Gasparri et al. 2010), this new AGB map represents a significant improvement in terms of modeling predictability and covered spatial extent (generated by applying traditional regression techniques vs. Random Forest, and applied on Landsat vs. MODIS imagery). Thus, this AGB map represents a significant advance in terms of information availability for this region. The exploration about the factors that control regional patterns of AGB suggests principally a climatic control by temperature (the

Table 2 Kendall's correlation coefficients (τ) between twelve independent variables (biophysical and human factors) and four dependent variables (biomass and woodland fraction)

	PPT	PPT: PET	Seasonality	Mean annual temp.	Coldest month temp.	Annual ground frost	Soil texture	Dist. to urban areas	Dist. to main roads	Dist. to cultivation	Road & trail length	Number of "puestos"	Mean AGB − 1.96 SD	Mean AGB	Mean AGB + 1.96 SD	Woodland fraction
PPT		0.84	−0.32	−0.43	−0.29	0.28	−0.01	−0.27	−0.16	−0.37	−0.19	−0.06	0.07	0.07	0.06	−0.14
PPT:PET			−0.48	−0.56	−0.43	0.41	−0.06	−0.33	−0.20	−0.47	−0.19	−0.10	−0.01	0.00	0.02	−0.21
Seasonality				0.51	0.50	−0.49	0.11	0.36	0.19	0.50	0.17	0.28	0.29	0.24	0.11	0.33
Mean annual temp.					0.83	−0.79	0.22	0.31	0.25	0.55	0.08	0.10	0.21	0.26	0.23	0.14
Coldest month temp.						−0.91	0.26	0.29	0.23	0.55	0.07	0.11	0.32	0.39	0.32	0.12
Annual ground frost							−0.27	−0.26	−0.23	−0.52	−0.07	−0.10	−0.29	−0.38	−0.34	−0.09
Soil texture								0.09	0.01	0.12	−0.07	−0.05	0.08	0.14	0.14	0.04
Dist. to urban areas									0.17	0.36	0.02	0.07	0.14	0.10	0.01	0.19
Dist. to main roads										0.22	−0.05	−0.04	0.11	0.13	0.12	0.09
Dist. to cultivation											0.09	0.22	0.24	0.26	0.18	0.31
Road & trail length												0.07	0.05	0.03	−0.01	0.08
Number of "puestos"													0.13	0.02	−0.10	0.33

Values lower than |0.05| were not significant ($p < 0.05$); $n = 570$. Acronym: PPT:PET, annual ratio between precipitation and potential evapotranspiration

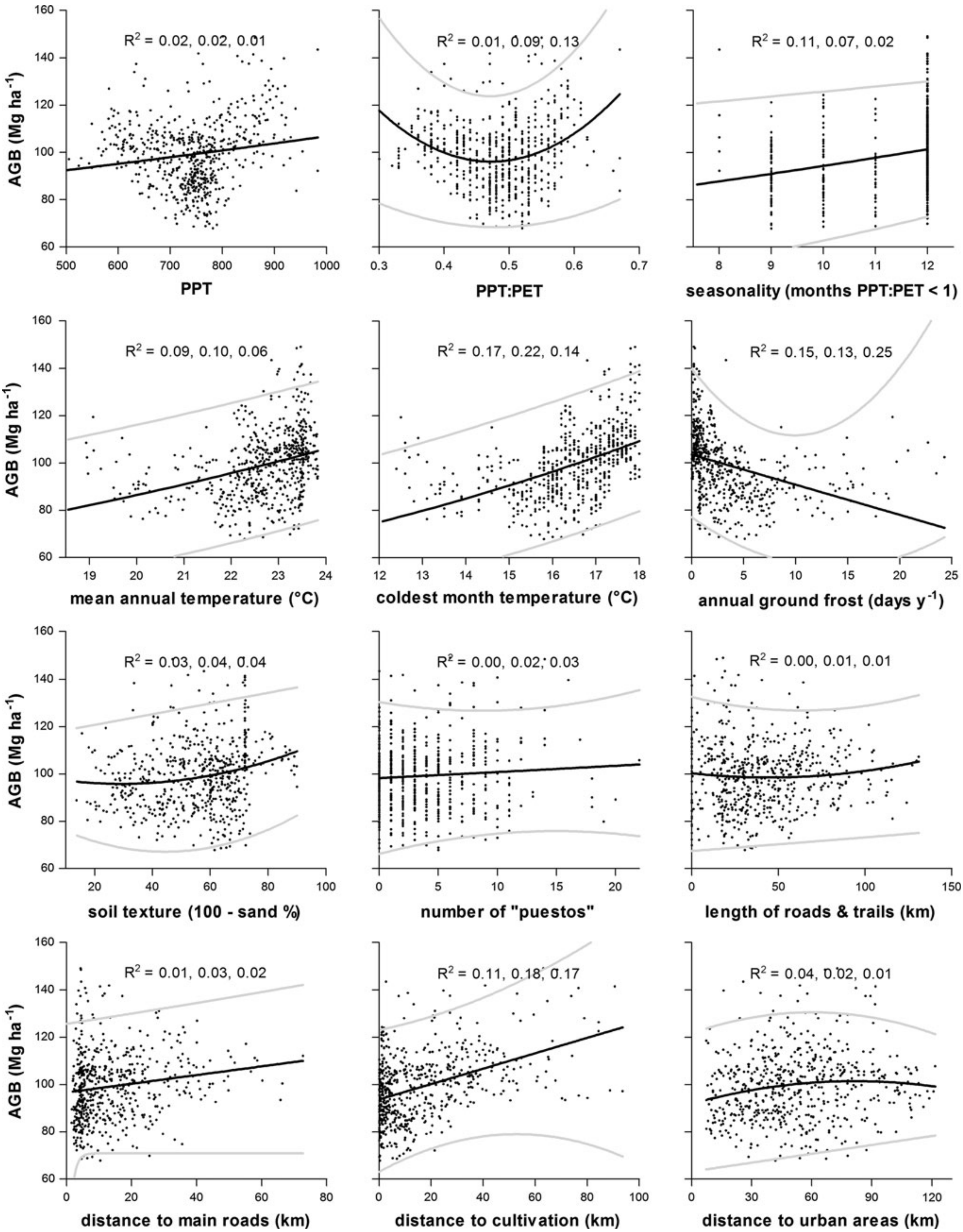

Fig. 3 Relationship between AGB and the twelve biophysical and human factors. Points represent each mean AGB value of the 570 grid cells, and lines the models for the highest values (mean +1.96 SD), mean, lowest values (mean −1.96 SD)

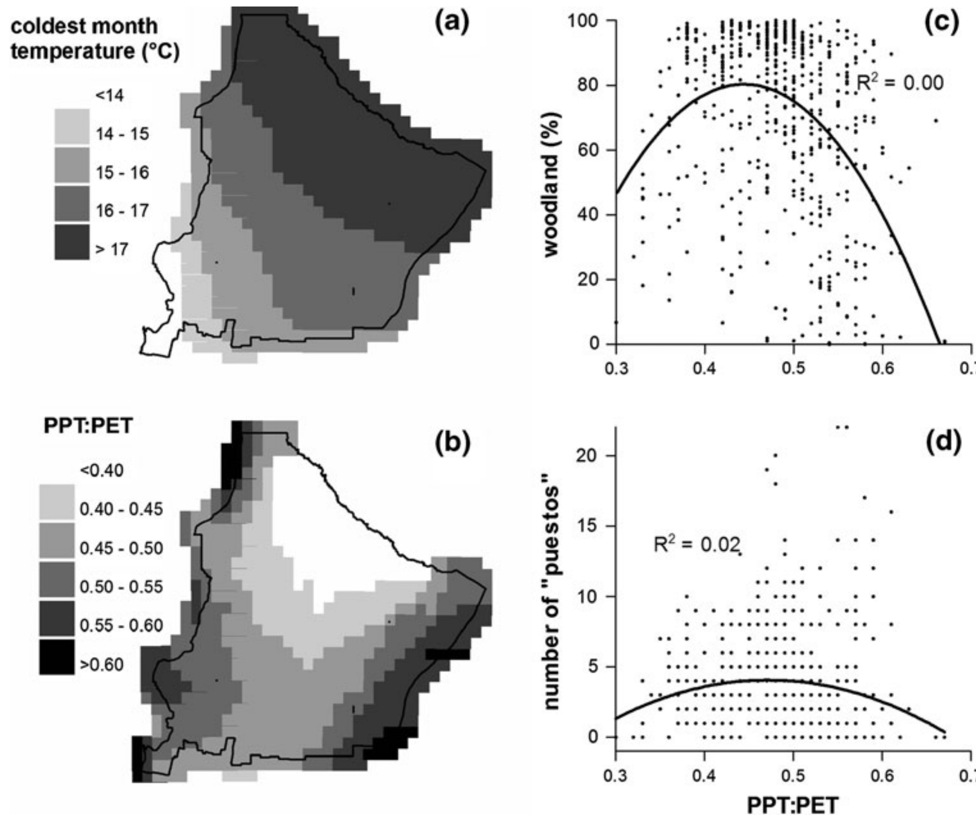

Fig. 4 Map of regional variation of the main biophysical variables under discussion PPT.PET (**a**) and (**b**): T° of coldest month (**b**). Plots of relationship between % of woodland cover in relation to the PPT:PET (**c**) and number of "puestos"(**c**)

colder the temperature, the lower the AGB) and secondary, by land use and accessibility.

AGB estimates and mapping

The obtained land cover map (Fig. 2a) was highly accurate and adequate to identify woodland areas, on where the AGB model was later applied. The accuracy of the AGB map developed here is close to those recorded—following similar methodological approaches for temperate forests in North America (Baccini et al. 2004), boreal forests in Russia (Houghton et al. 2007), moist tropics in Africa (Baccini et al. 2008), and the Amazonia (Saatchi et al. 2007).

Our results showed that the spectral response of vegetation during the dry season would provide the key information for biomass mapping. The low photosynthetic activity of grasses and shrubs during this season would permit to relate NDVI to presence of trees, in agreement with a previous study in the Amazon basin (Saatchi et al. 2007) and the Dry Chaco (Gasparri et al. 2010). Differences in the phenological cycle between grasslands, shrubs, and trees in the region can be explained by their differences in the use of water and affectation by frost. While grasses, forbs, and small shrubs explore the topsoil layer, trees can explore deeper profiles, reaching in some cases the water table (up to 16 m or more; De Gasperi 1959). Understory vegetation lose green leaves abruptly when water become scarce and also when temperatures descend from the freezing point, and trees retain green leaf until the moment of greatest evapotranspirative demand (spring). We argued that the use of NDVI values recorded in the dry season as independent variables to map AGB allow a functional interpretation of the ecosystems, contribute with theoretical support for the model, and provide potential extrapolation for other dry woodlands and forests.

Woodlands degradation received globally poor attention (le Polain de Waroux and Lambin 2012). It should be considered that in the Dry Chaco, besides deforestation, other forest use that promotes degradation cannot be monitored due to the lack of suitable methods. The available studies about degradation for the Dry Chaco are oriented to determine impacts in vegetation and also carbon stock but at local scales (Abril and Bucher 2001; Bonino 2006; Macci and Grau 2012). Complementary, the results of this study could constitute an initial step to assess regional woodland degradation and to develop a monitoring system.

AGB regional patterns

The analysis and interpretation of the controls over AGB regional patterns (Fig. 3) have to be done under consideration that the Dry Chaco is one of the less modified subtropical dry woodlands (Baldi et al. 2013). According to our results, the main factors explaining AGB regional patterns would be climatic rather than human. The relationships of the AGB with coldest conditions (given by temperature in the coldest month, number of days with frost, and mean annual temperature) suggest an energetic limitation for the AGB accumulation. These results are consistent with preliminary analyses for the region using phenology estimates from remote sensing, which pointed out temperature as the principal driver of productivity (season length, annual and growth season integrals of the EVI). Temperature was suggested as a main control over biomass accumulation in tropical moist forest (Raich et al. 2006), but for the Dry (and warm) Chaco, this results is somehow unexpected. A complementary interpretation could be that regional land use history would partially covariate with the Southwest (cold)–Northeast (warm) temperature gradient (Fig 4a), accentuated the spatial association between temperature and AGB. Cattle ranching since the XIX century (Morello and Saravia–Toledo 1959) and deforestation since the late 1970s (Gasparri and Grau 2009) were concentrated in the west sector of the study area, coinciding with the coldest areas.

Surprisingly for a dry ecosystem, the water availability (PPT:PET) would not be determining the AGB. One interpretation is that, within the encompassed water availability gradient (500 to 1,000 mm year^{-1}), this factor would not be the main limitation for the AGB accumulation, in agreement with other studies dealing with tree cover (Bucini and Hanan 2007; Groen et al. 2011; Baldi et al. 2013). Again, a complementary interpretation is that the relation between PPT:PET and AGB may be obscured by land use factors. The expected positive relation between PPT:PET and AGB could be masked by two aspects: (a) the underrepresentation of the less degraded woodlands due to the land use and deforestation history in the most humid sector and (b) the degradation by the concentration of "puestos" under intermediate humidity conditions. These patterns are partially supported by the relation between the PPT:PET, the woodland cover, and "puestos" number (Fig. 4b–d).

The AGB relation with soil was not very strong but suggests that soils with less sand tend to support woodlands with higher AGB. Very sandy soils, however, do not support woodlands, like in the cases of grassy paleo river beds; in the other extreme, heavy soils have drainage limitations and commonly show salinity problems and a low tree cover.

Previous global analyses indicate that accessibility is relevant determining structural and functional modification of subtropical dry woodlands (Baldi et al. 2013). In the Dry Chaco, the relationship between AGB and the distance to main roads suggest a tendency of higher AGB in more isolated areas. In our opinion, the study area does not include contrasting accessibility situations, even when secondary roads and trails are considered. Additionally, (in spite of not incorporating into the analyses previous interventions), we can state that the accessibility of the territory was uneven until the last decades. North–South connections in the western sector prevailed over West–East ones, leading to a land use legacy on AGB that prevails up to present.

Previous works documented a woody cover decrees in the Dry Chaco partially attributed to forest degradation (Clark et al. 2010). In our study, distance to cultivated areas showed the strongest relation with AGB between the human factors (Fig. 3). Beyond explaining mean AGB values, the relationship of this distance to the locally highest AGB values (mean +1.96 SD) can represent: (a) cultivation promotes a direct loss of woodlands by deforestation, and also the adjacent woodlands degradation because of a triggering of secondary activities as charcoal production; or (b) cultivation expand over previously degraded areas by a long-time history of extensive cattle ranching and selective logging. The last option is compatible with the patterns described in Grau et al. (2008), in where deforestation took place over degraded areas and promoted in the surrounding areas the abandonment of traditional activities and consequently lead to a woody vegetation recovery.

Current empirical evidence about the consequences of deforestation over the remnant woodlands remains contradictory, indicating that agriculture expansion could either release them or intensify over them, human interventions (Foley et al. 2005, Grau et al. 2008). This relationship remains elusive also for the Dry Chaco case, with an uncertain interpretation of woodland degradation or regrowth in relation to the cultivation expansion process. Temporal trends of woodlands degradation would allow us to solve this point, but, unfortunately, there is no such data for the Dry Chaco. To partially solve this lack of information, future studies necessaryly need to assess the time evolution of the human uses of forest areas near agriculture. Additionally, temporal mismatches between MODIS data and biophysical and human databases might constrain the precision and stability of our results. In our opinion, current AGB regional patterns would depend on the long-term biophysical conditions and land use legacies. Thus, to what extent these problems overwhelm the recorded links in this study, remains to be explored.

Our results open questions about the potential impact of the climate change and land use over the carbon pool of Dry Chaco. Obviously, deforestation reduces the regional carbon stocks, but climate change (mainly thought temperature increase) coupled with a reduction of the land uses that promote degradation could increment the carbon pool of the extensive remaining woodland areas and partially compensate emission by deforestation.

Lessons to explore regional controls of AGB

The apparently counterintuitive results found for the Dry Chaco exemplify the theoretical and methodological challenges that regional studies face in the process of understanding the human and biophysical controls of current structural and functional traits of ecosystems. We suggest in this sense that predictability and generalization of causal empirical models would differ across different spatial scales according to (a) the representativeness of the entire range of structural and functional conditions within a region and the consideration of land use legacies, and (b) our capability to discriminate human from biophysical controls.

Local to landscape-scale studies have the opportunity to deal with biophysical and human sources of variability. Some studies explore biophysical controls by minimizing human interventions or, by the contrary, human controls by minimizing environmental variability (e.g., Lobell et al. 2010). Land use legacy strongly affects the result and interpretation of both previous approaches, but can often be controlled (Peters et al. 2006) or described in detail for a given study area (e.g., Asner et al. 2008; Seabrook et al. 2006). On the opposite extreme, continental to global-scale studies incorporate on a single analysis a wide range of land use legacies, reducing their impacts, and a large collection of cases minimizing either human or biophysical variability (e.g., Raich et al. 2006 used only old-growth forest stands). Regional-scale studies have to deal with relatively small collection of cases when minimizing sources of variability and with strong effects of land use legacies that make the disentangling of human and biophysical controls difficult. In our study case, we have two contrasting examples of this coupled effect. One is given by the woodland degradation association with the "puestos" pattern, which makes the relation between AGB and water availability (if real) difficult to identify or understand and that could be interpreted as a control transfer from an environmental to a human factor. The other is given by the covariation of the land use history (deforestation and degradation) with a temperature gradient that could accentuate the effect of this environmental factor. Thus, for regional studies, results may be in discordance with models arisen from upscale or downscale studies, demanding from them a prudent interpretation.

We suggest that researchers can disentangle regional complexity in structure and functioning by (a) revisiting and re-evaluating traditional geographical methods (Schimper 1903) based on natural history and narrative (e.g., Fensham 2008); (b) performing hierarchal studies that take into account multiple resolutions and extensions to identify the active variables at each scale; and (c) following a comparative approach between regions, minimizing thus the human or environment variability (e.g., Baldi and Jobbágy 2012).

Conclusions

Monitoring the current spatial patterns of the carbon balance of forests (under degradation or re-growth) demands urgently the generation of remote sensing methods (Sánchez-Azofeifa et al. 2009). Additionally, it is necessary to assess the causes of spatial and temporal variability of the carbon balance, to explore alternative pathways of land management, and eventually the maintenance of the natural and human capital.

The differences in phenology of trees, shrubs, and grasslands seem to be one of the aspects involved in establishing the relationship between AGB and spectral information in semiarid and sub-humid woodlands. A better understanding of plant phenology in the Dry Chaco region may help us to focus and support projects to map biophysical variables in the region (e.g., biomass) on the basis of ecosystem functioning. The AGB map obtained in this study would contribute to the refinement of the region carbon stock estimates, and the characterization of the woodlands degradation and conservation status.

In this study we present the first exploratory analysis about woodland AGB patterns at regional scale in the Dry Chaco. At this scale of analysis, temperature rather than land use constrained AGB, but more detailed scale studies are necessary to explore the effects of landscapes accessibility. Future identifications of causal relationships of degradation (AGB depletion) will be especially useful for a regional policy development concerning carbon emission reductions by deforestation and degradation (i.e., REDD+). Exploratory studies about the interactions of extensive cattle ranching and agriculture expansion are needed. Empirical approaches to understand the controls of AGB-like multiple regression and neural networks techniques could be useful to identify which variables are driving current ecosystems structural patterns at multiple spatial and temporal scales.

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