Agricultural Systems 149 (2016) 20–29

Contents lists available at ScienceDirect

Agricultural Systems

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

Productive performance of alternative land covers along aridity gradients: Ecological, agronomic and economic perspectives

Francisco Murray [a,b,*], Germán Baldi [b], Tamara von Bernard [b], Ernesto Francisco Viglizzo [c], Esteban Gabriel Jobbágy [b]

[a] Instituto Nacional de Tecnología Agropecuaria (INTA), AER San Luis, Ruta 20 km 4.55 tramo R. Hernandez en rotonda Cuarto Centenario, 5700 San Luis, Argentina
[b] Grupo de Estudios Ambientales - IMASL, UNSL & CONICET, Ejército de los Andes 950, D5700HHW San Luis, Argentina
[c] INTA Centro Regional La Pampa - CONICET, Av. Spinetto 785, 6300 Santa Rosa, Argentina

ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 3 June 2016
Accepted 4 August 2016
Available online xxxx

Keywords:
Chaco
Espinal
Pastures
Natural vegetation
Crops
Farming costs

ABSTRACT

The replacement of natural vegetation by pastures and extensive crops is generally driven by economic incentives and supported by technology improvements and multiple subsidies. However, towards areas of increasing aridity the productive performance of these replacements may decline from all perspectives – ecological to agronomic to economic – due to intrinsic differences in the structural and physiological adjustment of natural and cultivated vegetation to reduced and fluctuating water availability. We compare natural woody vegetation, perennial C4 pastures and annual crops (maize, soybean and wheat) along a gradient of decreasing precipitation (900–400 mm of annual mean) encompassing the current agricultural frontier of the Dry Chaco and Western Espinal ecoregions of South America. We assess (i) aboveground net primary productivity (ANPP) (ii) yields of product dry mass, edible energy and protein outputs and, (iii) economic gross profits and return of investment. We linked climatic with yield data from national statistics, field trials and empiric models, together with productive parameters and market prices obtained from local consultants and economic bulletins. Maize achieved the highest ANPP of all vegetation covers (+42% in average compared to the rest) along the entire precipitation gradient, while the rest of the crops were very similar to natural vegetation. Pastures approached the ANPP of natural vegetation in the humid range, but had the lowest performance below 700 mm (−15%). Along the entire precipitation gradient, maize was outstanding in mass and edible energy yield while soybean was so in protein production. Soybean had the highest gross profit per hectare (+50%) and total capital return of investment (+70%). Pastures offered the highest functional capital return of investment (+98%; without fixed capital, infrastructure and land value costs), explaining their relevance at the onset of the deforestation process and the gradual prevalence of crops afterwards. While agronomic and economic incentives for natural vegetation replacement remain strong along the whole aridity gradient, crop choice rather than land use system seem to shape the key ecological process of net primary productivity.

1. Introduction

The replacement of natural vegetation – including forests, savannas and grasslands – with pastures and extensive crops has been the basis for increasing the production and appropriation of ecosystem goods that satisfy human needs (DeFries et al., 2004). The shortage and variability of rain that characterize arid and semiarid ecosystems (Noy-Meir, 1973), which occupy one fifth of terrestrial surface (UNESCO, 1977), have limited this replacement process due to high risks of productive failure of cropped systems in the short term, and higher degradation rates in longer terms (Foley et al., 2005). However, increases in the global demand of agricultural products (Alexandratos, 1999), the development of new soil and water management practices together with crop breeding and genetic modifications (Ahmad et al., 2012; Rockström, 2004; Sadras and Roget, 2004) and facilitated access to remote areas (Pfaff, 1999) strongly incentives current and prospective expansion in arid and semiarid regions (MEA, 2005).

These incentives for the replacement of natural vegetation involve complex tradeoffs that integrate a hierarchy of ecological, agronomic, and economic perspectives of the alternative land use systems (Kareiva et al., 2007), which can change from humid to arid conditions. From the ecological perspective, one of the most relevant issues is to what extent cultivation undermine the process of biomass production,

* Corresponding author at: Instituto Nacional de Tecnología Agropecuaria (INTA), AER San Luis, Ruta 20 km 4.55 tramo R. Hernandez en rotonda Cuarto Centenario, 5700 San Luis, Argentina.
E-mail addresses: murrayfrancisco@gmail.com (F. Murray), germanbaldi@gmail.com (G. Baldi), tvonbernard@gmail.com (T. von Bernard), eviglizzo@gmail.com (E.F. Viglizzo), jobbagy@gmail.com (E.G. Jobbágy).

http://dx.doi.org/10.1016/j.agsy.2016.08.004
0308-521X/

due to its intrinsic link with goods yield and other essential services of nature (Fisher et al., 2009). Opposite aspects may prevail depending on the intensity and length of water deficits: (i) the adaptive advantages of the natural vegetation with higher water use efficiency and stress-tolerance (Bacon, 2004) or (ii) the human-selected advantages of cultivated systems displaying lower respiration costs and responding more effectively to disturbances and subsidies (Begon et al., 2009). Thus, maximum primary production rates will likely be expected for natural vegetation towards drier conditions and for crops towards more humid ones. From the agronomic perspective, the priority is the partition of biomass towards harvestable products as food, fiber and fuel (Haberl et al., 2007). Generally, yield and harvest operations improve in more homogeneous crop structures (Evans, 1996). Since most of primary productivity is mainly used as food for human consumption (Vitousek et al., 1986), edible energy yield, probably followed by protein are the most appreciate quality factors (Drewnowski and Popkin, 1997). Finally from the economic perspective, the monetary benefits and mainly profits margin of resources invested emerge as the ultimate factor for decision makers in market-oriented economies (Gasparri et al., 2013). This fact becomes critical for ecosystem functioning and services as economic results maximization often displaces agriculture toward areas with lower performance from ecological or even agronomic perspectives (Fisher et al. 2009).

Vegetation covers in most populated regions of the world shows a relative dominance of rainfed crops in more humid areas, of pastures or double-purpose crops (fodder/grain) in intermediate conditions, and of natural vegetation towards extreme aridity unless irrigation is applied (Ellis et al., 2010; Grigg, 1974). Ecophysiological contrasts between these types of vegetation covers and their dominant functional type of plants suggest that high rates of photosynthesis and nutrients uptake to plant grow and production are favored in fertile and humid lands (Lambers et al., 1998). Opposedly, slow-grow and stress-tolerant species with more resource-use efficiency, structural tissues and roots tend to be increasingly favored in arid lands (Grime, 2006). Besides, tradeoffs between carbon gain and water loss suggest the presence of optimum ranges of stress intensity for each plant functional types (Solbrig and Orians, 1977). Thus, along a gradient of increasing aridity a sequence of optimum performance for fast growing annuals (crops), intermediately growing perennial grasses and forbs (pastures), and then for slow growing xerophytic woody plants (natural vegetation) can be expected. The result would be a progressive shift in advantages for annual crops, pastures, and natural vegetation, at least in the ecological process of biomass production (Hypothesis 1A - Fig. 1). However, the higher usable fraction and more favorable cost-value relationship of the produced biomass may likely imply advantages from an agronomic and economic perspective for annual crops above all other covers and for pastures above natural vegetation (Hypothesis 2, Fig. 1).

In this work we compared natural woody vegetation and pastures and crops as its replacement, with their corresponding mixed ranching-forestry, ranching and cropping land use systems. We explore the productive performance of these systems linking tradeoffs from three perspectives that range from the basic underlying ecological process of biomass production, to the agronomic process of harvesting goods, to the economic process of profit generation. The set of variables includes magnitude of aboveground net primary production, yield of commercial products (grain, meat, wood and charcoal) in terms of mass and edible energy and proteins, and gross profit and return on investment. These analyses were performed along a gradient of decreasing annual precipitation spanning from 900 to 400 mm, encompassing the two largest semiarid ecoregions of Southern South America, the Dry Chaco and Western Espinal. Diverse data sources were combined, including climate databases, field trials, yield records, empiric biophysical models, together with costs/prices information from local consultants and economic bulletins.

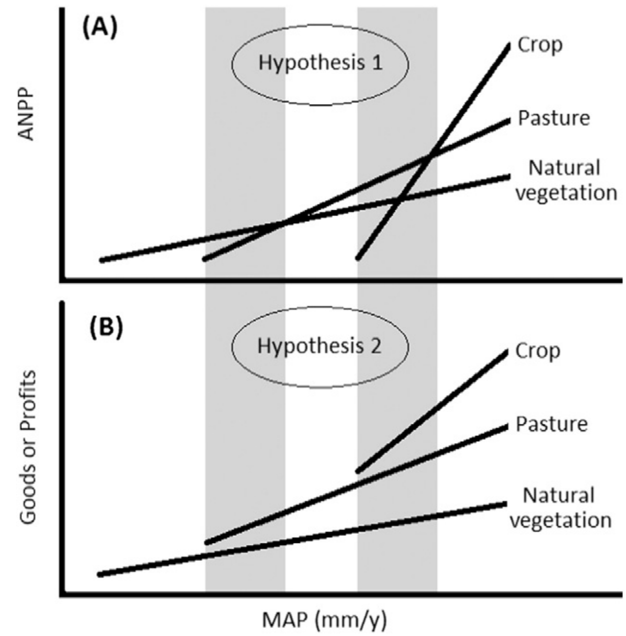

Fig. 1. Hypothesis regarding decreasing mean annual precipitation (MAP) effects on three vegetation covers from the perspective of (A) the ecological process of biomass production, and (B) the agronomic or economic process of goods or profits generation. A higher threshold of minimum MAP for crop vs. pasture cultivation is assumed. Gray zones show hypothetical MAP belts in which agronomic/economic criteria could favor vegetation covers with suboptimal biomass production.

2. Materials and methods

2.1. Study region

We focused our analysis in the semiarid belt of Argentina and Paraguay, which includes approximately 450,000 km^2 of the Dry Chaco and Western Espinal ecoregions, along a precipitation gradient from 900 to 400 mm year^{-1} (Fig. 2). This region is characterized by flat to slightly rolling topography, with predominance of Mollisols and Entisols developed on alluvial and eolian sediments. Predominant natural vegetation includes xerophyte woodlands and shrublands, alternated with transitions to savannas and pure grasslands stands (Cabrera, 1971) and with variable degrees of replacement with pastures and annual crops (Clark et al., 2010; Graesser et al., 2015; Vallejos et al., 2014). Traditionally, natural vegetation was used for cattle ranching, complemented with selective logging of wood for charcoal and others products of low aggregated value (Bucher and Huszar, 1999; Dussart et al., 2011; Karlin et al., 2004; Rueda et al., 2013). These forestry activities are normally characterized by low technology and manual work (Rueda et al., 2015; Turc and Mazzucco, 1998). Alternatively, the establishment of cultivated pastures of megathermal African grasses (C4 photosynthetic syndrome) has been progressively adopted due to their higher forage production and stocking rate capacity (Rueda et al., 2013; Stritzler et al., 2007). Under either natural vegetation or pastures, current ranching systems are characterized by extensive cow-calf activities, where young calves are sold for breeding and fattening in more favorable regions (Garbulsky and Deregibus, 2004; Morris and Ubici, 1996). These activities required infrastructure such as fences and watering points but have low dependence of external inputs (Laca, 2009; Magliano et al., 2015). Most recently, extensive cropping systems (mostly soybean, maize and wheat) expanded throughout the region with a strong commodity export orientation (Leguizamón, 2014), copying the more humid Pampas productive model (highly dependent on machinery and agrochemical inputs) with minor adjustments to local arid conditions (Viglizzo et al., 2011).

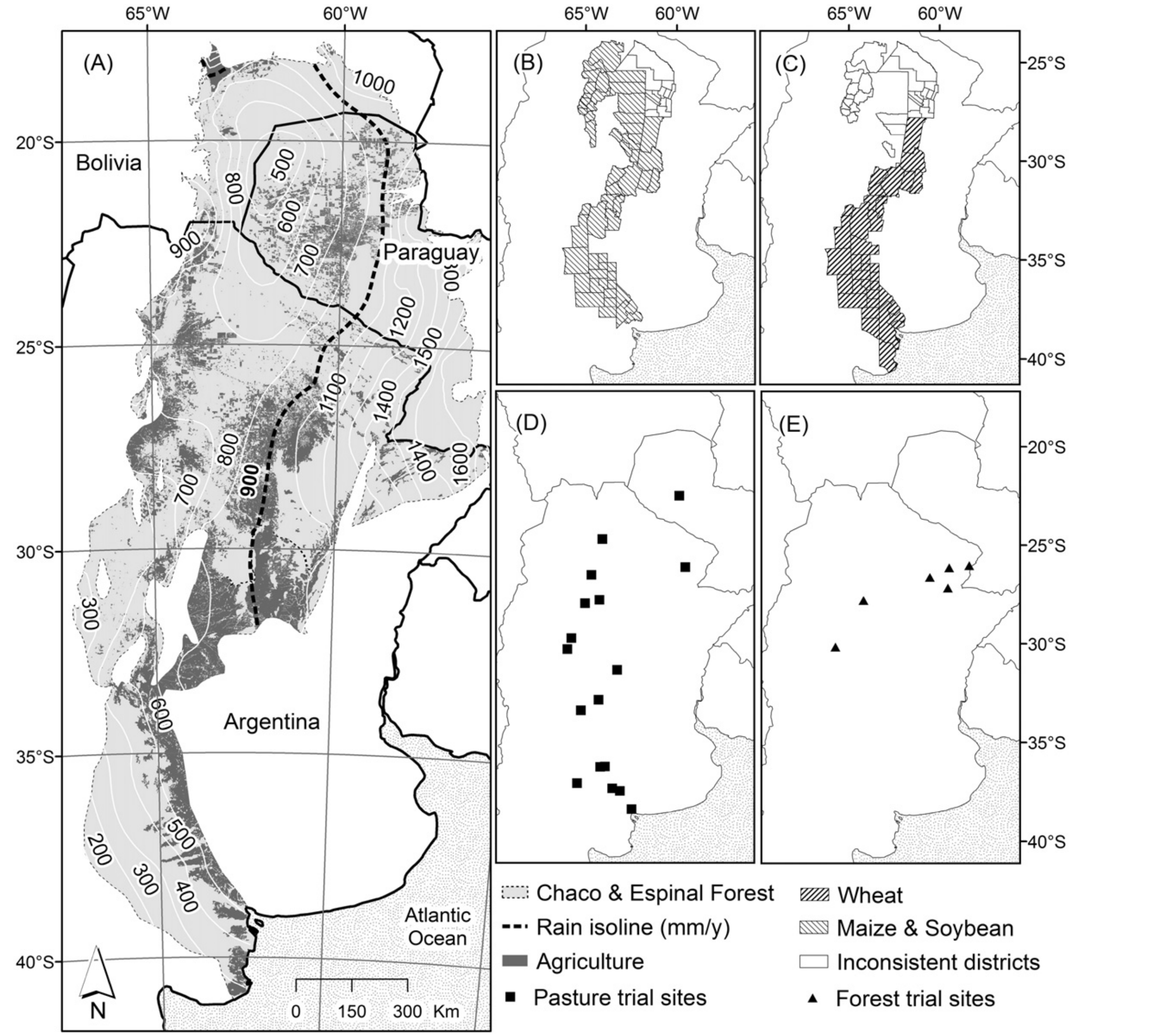

Fig. 2. (A) Semiarid belt of Argentina and Paraguay with <900 mm y^{-1} of rain within the Chaco and Espinal ecoregions in light gray (Olson et al., 2001), with agricultural areas in dark gray (crops and pastures) and mean annual precipitation isolines. (B and C) Political districts from which crop yield data were obtained (including those mentioned but with inconsistent yield data). (D) Pasture cut-trial and (E) tree growth-trial sites.

2.2. Data source and estimation procedures

We compared five vegetation cover types belonging to three land use systems represented by (i) rainfed crops comprising soybean, maize and wheat, corresponding to pure cropping systems; (ii) implanted perennial pastures corresponding to cattle ranching systems; and (iii) natural vegetation corresponding to mixed cattle ranching-forestry systems. For each vegetation cover, we described the magnitude of aboveground net primary production (ANPP), average yield of commercial products (grain, meat, wood and charcoal) including their output in terms of mass, edible energy and proteins; and economic direct costs and profits. The usable fraction and dietary composition data of grains and livestock was obtained from the USDA Nutrient Database for Standard Reference (USDA, 2011). Wood and charcoal composition was based on FAO (FAO, 1983).

For rainfed crops, we used county-level yield annual statistics for the 2001–2012 period, provided by the annual survey of the National Ministry of Agriculture of Argentina (MAGyP, 2012). Irrigated land, which occupied <5% of the territory, was not considered in order to avoid the confusing imprint of water subsidies. We assumed a negligible contribution of winter-summer double cropping practices on yield data due to the low incidence of these rotations in water limited conditions. We calculated the mean ANPP of crops as their peak biomass derived from the ratio of grain yield to harvest index, which was assumed to adopt values of 0.45 for maize, 0.37 for soybean and 0.35 for wheat (Carcova et al., 2004). To take into account the higher energy requirement of oil and protein synthesis in soybean and wheat grains compared with maize, grain yield data were transformed to “maize equivalent biomass”. For this purpose, we used a correction factor of 1.4 in soybean and 1.1 in wheat, based on the amount of glucose required to synthesize these grains compared to maize (Sinclair and de Wit, 1975). Stubble biomass of all crops, as well as pasture and forest debris, which are composed mostly of carbohydrates, were considered equivalent to maize grain in their energy content.

For pastures we estimated ANPP using data from 26 sites distributed throughout the region. Published data from two- to ten-year long cutting trials corresponded to the typical pastures planted in the region (mainly *Eragrostis curvula* and *Digitaria eriantha* in the south, the same species together with *Cenchrus ciliaris*, *Tetrachne dregei* and *Panicum* *coloratum* in the center, and *Cenchrus ciliaris*, *Panicum maximum*, *Chloris gayana*, *Brachiaria brizantha* and *Cynodon nlemefuensis* in the north; Appendix A). For each site we considered the average annual accumulated biomass of all cutting trials without species differentiation and only from treatments with low or null fertilizer inputs, as typically found in real pastures. These data were compared to the regional model for mixed C3-C4 grasslands developed by Sala et al. (1988) for North America.

Livestock productivity was estimated based on forage biomass production applying an energetic balance as follows: biomass use efficiency was set to 50% and metabolic fraction of gross energy (3.608 Mcal kg^{-1}) was assumed to decrease linearly between 65% to 55% from 900 to 400 mm of MAP, according to expected shifts in pastures species composition and increasing senescence periods with aridity (Avila et al., 2013; Stritzler, 2008). Energy requirements were set in 1.28 equivalent animal units (AU) for each breeding cow, which is equivalent to cattle units (Cocimano et al., 1975). This equivalent value results from a herd producing 6-month-old female and male calves of 150 and 160 kg, with 1 bull for every 25 cows, and an annual rate of replacement and mortality of 20% and 5%, respectively. We assumed 80% of potential weaning calves to breeding cows ratio, which is considered a conservative and achievable value even for the most arid Chaco with appropriate management conditions (Ferrando et al., 2005).

For natural woody vegetation, total ANPP and merchantable wood production were estimated using two different complementary approaches. For ANPP, we applied a global empirical model that correlates total ANPP of natural woody vegetation to climatic variables (Del Grosso et al., 2008). For merchantable wood production, calculations were based on local data from direct measurements in eight woodland stands distributed along a precipitation gradient and Official estimations (Appendix A). To contrast the performance of these local data related to the global model we estimate tree-only ANPP from the original merchantable wood production data applying successive upscaling factors that consider other plant components (Appendix A).

The production of goods from natural woody vegetation involved forestry and cattle ranching items. For forestry, our previous global and local data estimations implied 70% to 54% of total ANPP coming from trees from 900 to 400 mm, with 50% of harvestable biomass, coincident with field measures of similar dry forests (Singh and Singh, 1991). For this harvestable biomass fraction, we estimated a high-end achievable production scheme, according to the selective logging management with uneven tree sizes recommended by the Forest Department of Chaco Province, Argentina (Grulke et al., 2007). According to this scheme, the proportion of merchantable wood production obtained as roundwood, posts and firewood to produce charcoal was set in 2%, 19% y 79% with 900 mm, changing linearly with increasing aridity to 0.5%, 5% and 94.5% with 400 mm, respectively, based on Coronel de Renolfi and Brassiolo (2008). Charcoal efficiency yield from firewood was set in 5:1 (FAO, 1983; Rueda et al., 2015). For ranching, cattle productivity was calculated following the same procedure and parameters used for pastures, assuming an average forage availability in the understory of 30% of what is estimated for pastures due to lower grass cover, growth and accessibility (Blanco et al., 2005; Grau et al., 2008; Kunst et al., 2012).

Mean annual precipitation values assigned to each productivity data came from the "Ten Minute Climatology data base" (CRU CL 2.0; New et al. (2002)) depicting point-based averaged values for 1961–1990 period. Average precipitation values assigned to political districts were calculated considering only points lying over the agricultural cover, according to recent maps (UMSEF, 2008). For field data with an explicit location we used the closest precipitation values from the same database. Average differences between observed mean annual precipitation for 103 meteorological stations located along the region for the period covered by crop yield data (2001 − 2012) and CRU period was only 2% above CRU values, indicating that this database was also an appropriate reference for that temporal span.

2.3. Economic evaluation

The land use systems associated with each vegetation cover type were economically evaluated by means of (i) gross profit (GP) per unit of land (gross income minus operating and amortization costs per hectare), (ii) total return on investment (tROI, gross profit to total capital ratio), and (iii) functional capital return on investment (fROI, gross profit to operative and amortization costs ratio, without fixed capital, infrastructure and land value). With these two different Indices of ROI we attempted to describe macro vs. micro-business perspectives, usually associated with the perspectives of investors vs. farmers, explained by variation in capital and land resources (Gasson, 1973). Productive parameters were adjusted to regional environmental conditions; derived costs were estimated from local prices of labor, inputs and services required, while gross income were calculate multiplying market price by the quantity of goods produced. In all cases we used average market values for 2008–2011-year period, based on data availability in economic bulletins and government statistical databases and on its relative stability. Values and taxes of land were derived from linear correlation between mean annual precipitation and data from real-estate market publications or government decrees, respectively, according to their productive aptitude (Appendix A). Maintenance costs in all cases included 12,000 km of mobility, 2% of reposition value of equipment and structure reparation and 2% of gross income as administrative costs. Equipment and structure consisted of fences, storehouse, watering hole and a pickup truck. A sensitivity analysis of the economical outputs was made to determine the impact of alternative assumptions in trade and operative costs.

Crop productive parameters involved the use of no-till farming, genetically modified seeds for maize and soybean, and agrochemicals for weed and pest control. The type and quantity of inputs and services, as well as their prices and market values of grains were defined following prescriptions for similar regions based on a national reference publication (Margenes Agropecuarios, 2012). Farm values of grains were calculated from "Free Alongside Ship" (FAS) prices, subtracting trade costs including transport to an average distance to the nearest port of 500 km. Fertilizer application were not considered in gross profit calculation, except for the sensitivity analysis, due to the prevalence of low-input farming schemes in semiarid of Argentina (Viglizzo et al. (2001).

Pastures productive parameters involved direct costs of a full-time employee for every 800 animals and additional labor from one employee for 3 months per year, pasture renewals every 5 years, bull replacements every 4 years, veterinary services and infrastructure maintenance as prescribed for cattle ranching activities in similar areas (Margenes Agropecuarios, 2012). Farm value of ranching goods were calculated as a weigh average from the sale of calves – excluding those retained for cow replacement – and from discarded cows and bulls (Margenes Agropecuarios, 2012), subtracting trade costs including minus a fixed proportion for commissions and transport assuming an average transport distance to markets of 200 km for the whole region (Albrieu et al., 2009).

Natural woody vegetation productive parameters considered wood harvest, charcoal making and cow-calf activities. Machinery costs per unit of wood harvested were set according to operative times measured in traditional labor-intensive systems (Turc and Mazzucco, 1998). Labor costs per unit of wood or charcoal product were set from minimum salary and social security contribution taxes established by the national government of Argentina for the year 2010 and 2012 (MTEySS, 2010, 2012), retroactively adjusted according to inflation indices to estimate the average for 2008–2011 year period (INDEC, 2014). Farm values for wood and charcoal products were obtained from the Forest Department of the Chaco Province of Argentina statistical database, in which case transportation and commission costs were already discounted (DFPCH, 2011). Cattle ranching costs and farm-gate prices were similar to what was described for pasture systems.

3. Results

We sequentially describe our findings concerning ecological, agronomic and economic perspectives for each vegetation cover type, in all cases moving from humid to arid conditions. Despite the broad gradient used for regression models construction, most analyses encompass the cultivated range from 900 to 500 mm of mean annual precipitation (MAP) in which all cover types coexisted, yet a few extended down to 400 mm where summer crops were not present. Overall, we found that, opposing to all our hypotheses, summer crops outperformed all the other cover types even in the most arid edge. Within this group of crops, maize and soybean performed better depending on the perspective being considered. The magnitude of contrasts created by crop choices and cover types was highly dependent on climate.

3.1. Ecological perspective: magnitude of ANPP

The magnitude and rate of decline of ANPP with increasing aridity showed higher contrasts between crop species than land cover or land use type (Fig. 3 a & d). The ANPP of maize exceeded by ~4.0 Mg ha^{-1} y^{-1} the mean of all other covers (+42%) along the entire cultivated range of MAP. Also, maize outperformed the rest of the vegetation covers even when only the fraction of ANPP remaining in the field after harvest, grazing or logging was considered (the annually prorated remaining biomass in case of logging). The maize remains exceeded pastures by 1.9 Mg ha^{-1} y^{-1} (+36%), soybean and wheat average by 2.1 Mg ha^{-1} y^{-1} (+40%) and natural woody vegetation by 2.1 Mg ha^{-1} y^{-1} (+40%), with remaining fractions representing 55%, 70%, 55%, 63% and 60% of total ANPP, respectively (data not shown).

Opposite to our expectations, pastures did not exceed the ANPP of the other cover types in any range of MAP values, falling behind maize by 3.6 Mg ha^{-1} y^{-1} (−48%) in the most arid cultivated edge from 600 to 500 mm (Fig. 3 b and d). Only for MAP > 700 mm pastures had higher ANPP than wheat and matched that of natural vegetation and soybean, while for MAP from 700 to 400 mm showed an average biomass gap of −0.7 Mg ha^{-1} y^{-1} (−15%, p = 0.025). Also, pastures showed a sharper decrease in ANPP of that observed in precipitation (−52% vs. −44% shift) and of that observed in crops and natural vegetation (−40% and −41%). However, compared to the regional model for mixed C3-C4 natural grasslands developed by Sala et al. (1988) for North America, the overall rate of ANPP change with aridity of C4 pastures was 1.5 times higher (9.3 vs. 6 kg ha^{-1} y^{-1} mm^{-1}), as a result of higher ANPP (+2.2 Mg ha^{-1} y^{-1}) at 900 mm and similar ANPP levels at 400 mm of MAP.

Average total ANPP of natural woody vegetation computed according to the global model (Del Grosso et al., 2008) was similar to the figures for soybean and wheat but fell behind maize crop by 3.8 Mg ha^{-1} y^{-1} (−40%) (Fig. 3 c and d). According to field trials, the ANPP of trees represented on average 67% of the total ANPP (3.9 vs. 5.4 Mg ha^{-1} y^{-1}). Assuming that non-tree ANPP of natural vegetation, that mostly includes herbaceous, forbs and epiphyte plants, could be roughly estimated as the difference between the former models, it would correspond to approximately 1.8 and 1.5 Mg ha^{-1} y^{-1} in 900 and 400 mm of MAP, which constituted almost 100% to 50% of the forage assumed for livestock feeding in the corresponding economic model, for the same MAP values.

3.2. Agronomic perspective: goods, energy and protein

Crops produced remarkably higher amount of goods in terms of mass, energy and protein per unit of area compared to the other land use systems, even at the arid extreme of their distribution (Table 1).

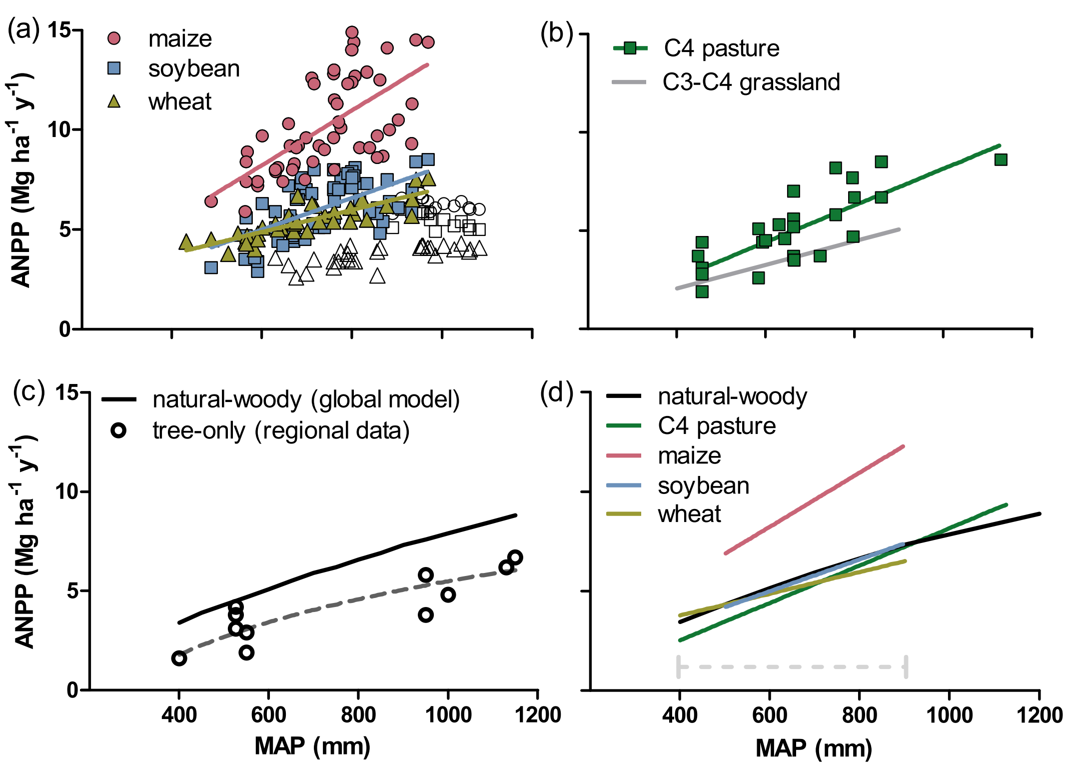

Fig. 3. Mean annual net primary productivity (ANPP) related to mean annual precipitation (MAP) for crops, pastures and natural vegetation, expressed as tons of dry mass per hectare per year. Dry mass values for soybean and wheat were adjusted to maize equivalents accounting for their higher energy content of oil and protein. Models represent (a) county-level records for crops, including maize ($y = 0.0137\,x - 0.0172$ $r^2 = 0.41$, $p < 0.0001$), soybean ($y = 0.0079\,x + 0.2592$, $r^2 = 0.37$, $p < 0.0001$) and wheat ($y = 0.0055\,x + 1.5790$, $r^2 = 0.69$, $p < 0.0001$), with hollow points for discarded inconsistent data; (b) field trials for megathermal pastures ($y = 0.0093\,x - 1.1720$, $r^2 = 0.60$, $p < 0.0001$) and the mixed C3-C4 grassland model from Sala et al. (1988) developed with data from North America; (c) empirical global model for tree-dominated ecosystems from Del Grosso et al. (2008) ($y = 0.1665\,x^{1.185/\exp(0.000414\,x)}$, $r^2 = 0.40$) contrasted with tree-only data derived from regional data ($y = 9.343\log(x) - 22.48$, $r^2 = 0.81$); and (d) synthesis of main adjusted models for the different vegetation cover types (excluding tree-only and grassland), with a horizontal gray dotted bar encompassing the range from 900 to 400 mm of mean annual precipitation where analyses were made.

Table 1
Elemental composition of goods derived from different vegetation cover types; together with their mass, energy and protein annual yield in 900 and 500 mm of precipitation edges of the aridity gradient.

Cover	Use	Goods	Composition				Goods annual production					
			Dry matter	Usable fraction	Energy	Protein	Mass		Energy		Protein	
			% mass	kg kg^{-1}	Mcal kg^{-1}	% mass	Mg ha^{-1}		Mcal ha^{-1}		kg ha^{-1}	
							900 mm	500 mm	900 mm	500 mm	900 mm	500 mm
Maize	Cropping	Grain	90%	1	4.1	11%	5.554	3.082	20,345	11,288	525	291
Soybean	Cropping	Grain	90%	1	4.9	40%	2.384	1.364	10,471	5992	856	490
Wheat	Cropping	Grain	90%	1	3.8	14%	2.211	1.466	7521	4989	273	181
Pasture	Ranching	Cattle	41%	0.68	6.8	39%	0.160	0.067	303	128	17	7
Natural woody	Ranching	Cattle	41%	0.68	6.8	39%	0.048	0.020	91	38	5	2
vegetation	& forestry	Roundwood	85%	1	4.1	-	0.589	0.084	2053	293	-	-
		Post	85%	1	4.1	-	0.058	0.008	203	28	-	-
		Charcoal	90%	1	7.2	-	0.460	0.299	2988	1938	-	-

Moreover, crops showed the lowest sensitivity to the increasing aridity (−44% shift), with an average a reduction of just −40% in the mass of goods produced from 900 to 500 mm, compared to decline of −65% in forestry products (resulting in part from the higher proportion of wood burnt for charcoal) and −58% in cattle products. Maize was the prominent crop in relation to mass and edible energy production, with average yields along all precipitation gradient of 2.3 and 2.2 times compared to the other crops (4.3 vs. 1.9 Mg ha^{-1} y^{-1} and 15,817 vs. 7243 Mcal ha^{-1} y^{-1}), 5.5 and 245 times compared to natural vegetation (0.8 Mg ha^{-1} y^{-1} and 65 Mcal ha^{-1} y^{-1}, without considering 3751 Mcal ha^{-1} y^{-1} from non-edible woody products), and 38 and 73 times compared to pastures (0.1 Mg ha^{-1} y^{-1} and 215 Mcal ha^{-1} y^{-1}), respectively. With half of the mass of maize, soybean was the prominent crop in protein production, with 2.1 times compared to the average of the other crops (673 vs. 317 kg ha^{-1} y^{-1}), 182 times compared to cattle products from natural vegetation (3.5 kg ha^{-1} y^{-1}) and 55 times compared to cattle products from pastures (12 kg ha^{-1} y^{-1}).

3.3. Economic perspective: gross profit, returns on investment and sensitivity analysis

Economic results strongly varied between vegetation cover types and especially within crop species, in interaction with aridity and business perspective. Considering gross profit per unit of land (GP, gross income minus operating and amortization costs per hectare), soybean followed by maize were the prominent covers along the whole aridity gradient, while wheat had the lowest with also a negative result in the most arid range (Fig. 4 a). Livestock grazing on pastures had an intermediate performance in more humid conditions, but outperformed wheat and natural vegetation in the arid range from 500 to 400 mm. While GP of natural vegetation halved that of pasture systems, livestock grazing of the forest understory still explained 50% of its economic results (18.8 of 40.0 US$ ha^{-1} in average along all precipitation gradient) with just 4% of its total mass production (Table 1), thus evidencing the extremely poor performance of the forestry business. The return on investment (ROI) fulfilled by these GP were also contrasting depending on vegetation cover type and whether referred to total (tROI, Fig. 4b) or just functional capital (fROI, Fig. 4c), the latter comprising only operative and amortization costs. Soybean tROI double the rest of the alternative covers types along the entire cultivated range, and was very close to equal to a hypothetical opportunity cost of a bank interest rate of 0.05 US$ US$$^{-1}$ (Fig. 4 b). Only towards 400 mm of MAP pastures and natural vegetation rose up to almost 0.045 and 0.035 US$ US$$^{-1}$, respectively, due mostly to higher decreases in land values than decreases in GP with higher aridity. Oppositely, from the perspective of fROI, pasture had the highest performance, being twice the average of natural vegetation and soybean (Fig. 4 c).

A sensitivity analysis showed that the ranking of economic results was highly dependent of changes in several trade and operative costs, primarily in transport, together with seed prices and potential fertilization needs in agriculture and labor costs in forestry (Table 2). Transport cost equated on average 70% of total operative costs of maize, 50% of wheat, 35% of soybean, only 3% of livestock and almost 85% of forestry products, while it reduced farm-gate prices related to market price only 16% in soybean but 30% in maize and wheat. The partial potential

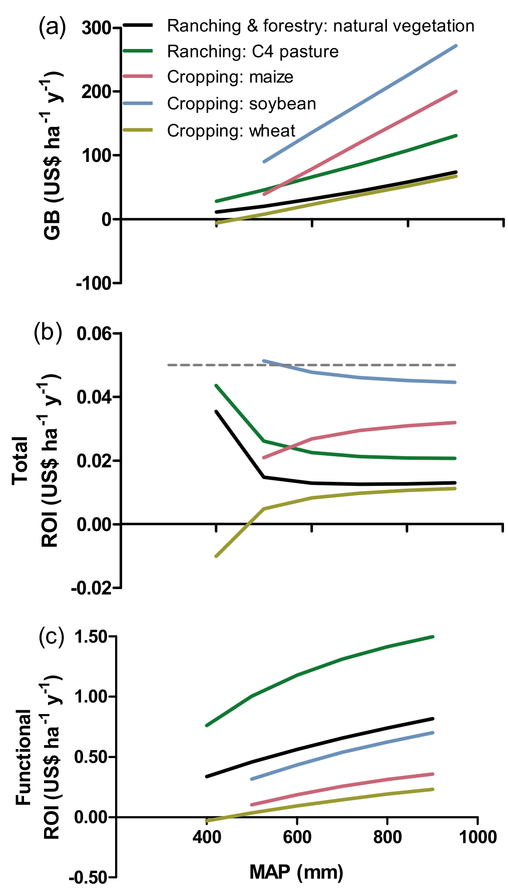

Fig. 4. Economic results for each vegetation cover type related to mean annual precipitation (MAP) in terms of (a) gross profit (GP) per unit of land (gross income minus operating and amortization costs per hectare), (b) total return on investment (ROI) (gross profit to total capital ratio) and (c) functional capital return on investment (gross profit to operative and amortization costs ratio). Models were derived using ANPP estimations from national statistics, field trials and empiric models, together with market prices and specific productive parameters of each system. Gray dotted line in (b) represents regular bank interest rate.

Table 2
Operative, trade costs and resulting farm-gate prices of goods derived from each vegetation cover type. (1) Fertilizer cost was only included in economic sensitivity analysis. The sum of trade costs and farm-gate prices for grains are equivalent to "Free Alongside Ship" (FAS) market prices for Argentina. All values are averages from 2008 to 2011 year period. AU: animal units. Transport distances of 200 and 500 km.

Cover	Use	Product	Operative costs									Farm-gate price	Trade costs	
			Seed	Agro-chemicals	Fertilizer$^{(1)}$	Machinery	Labor	Animal health	Bulls	Harvest	Maintenance & taxes		Commission & taxes	Transport
			US\$ ha^{-1} 500–900 mm	US\$ ha^{-1}	US\$ ha^{-1} 500–900 mm	US\$ ha^{-1} or Mg^{-1}	US\$ AU^{-1} or Mg^{-1}	US\$ AU^{-1}	US\$ AU^{-1}	US\$ Mg^{-1}	US\$ ha^{-1} 500–900 mm	US\$ Mg^{-1}	US\$ Mg^{-1}	US\$ Mg^{-1}
Maize	Cropping	Grain	70–86	54	55–76	49.0	-	-	-	9	25–36	86	7	44
Soybean	Cropping	Grain	33–43	58	15–22	64.2	-	-	-	22	26–37	221	11	44
Wheat	Cropping	Grain	33–41	31	37–106	46.3	-	-	-	12	22–30	110	7	44
Pasture	Ranching	Cattle	2.8	0.4	-	10.50	16.2	7	9.8	-	9–17	1340	101	31
Natural woody vegetation	Ranching & forestry	Cattle	-	-	-	-	16.2	7	9.8	-	8–13	1340	101	31
		Roundwood	-	-	-	*2.8*	*20*	-	-	-		70	-	44
		Post	-	-	-	*4.1*	*150*	-	-	-		220	-	44
		Charcoal	-	-	-	*20.4*	*60*	-	-	-		100	-	44

reduction of this factor to a half determined that maize economic results equated soybean due to its larger production mass, and that wheat equated pastures. For forestry products, similar 500 km transport cost than applied for grains absorbed 17% of market price of posts, 31% of charcoal, 40% of roundwood and almost 71% in case of firewood (0.018 US\$ kg^{-1} farm-gate price). In the case of ranching products, with shorter average transport distances of 200 km and higher values per unit of weight, this factor reduced farm-gate prices related to average market prices only 2%. Among operative costs, the highest in maize was seed (35%), being 30 times more expensive than grain vs. two times in case of soybean and wheat, thus only a half reduction of this factor determined that its economic results almost equated soybean, similarly to what was observed with transport costs reduction. Fertilization, which is still an uncommon practice in the current agricultural systems, will affect ROI levels even if half of the doses recommended to replace exported nutrients would have to be applied, with average tROI reductions to 0.9 and −1.5 US\$ US\$$^{-1}$ in case of maize and wheat, but only to 4.1 in soybean due to biological nitrogen fixation. Meanwhile, ranching and forestry average total systems operative costs represented only 46% and 27% related to crops, respectively. The highest operative costs in pasture were implantation and conservation (60%), while in natural vegetation the most important was labor (61%).

4. Discussion

The replacement of natural vegetation by crops is often linked to trade-offs between food supply, economic profits and multiple environmental costs (DeFries et al., 2004), specially in dry regions where the risk of productive failures and the likelihood of soil degradation are typically higher (Foley et al., 2005). In this context, our results challenge our first hypothesis as they revealed that crop choice (maize vs. others) exceeded land cover or land use type shaping a fundamental ecosystem attribute such as primary production, without any "ideal" intermediate productivity niche for pastures, and with natural vegetation standing out only where crops may not be viable at all. Supporting our second hypothesis, summer crops showed agronomic and economic advantages for maize and soybean, respectively, over pastures or natural vegetation. Interestingly, the performance of maize from the economic perspective was mostly undermined by a higher technology fee on seeds and higher transportation costs relative to grain prices, compared with soybean. However, pastures attained the highest returns on functional capital invested – only operative costs are considered – and the lowest relative transport cost (farm-gate price to transport cost), which could explain cattle ranching relevance at the beginning of land use transition in remote areas and for low capital land users (DeFries et al., 2006). Thus, our results reveal strong agronomic and economic incentives for deforestation even in the driest areas, supporting predictions of agriculture expansion in the coming decades (MEA, 2005) and challenging conservation efforts.

Though global analyses have shown that conversion of natural vegetation to agriculture cut biomass production (Bondeau et al., 2007; DeFries et al., 1999; Haberl et al., 2007) and carbon inputs (Guo and Gifford, 2002), except in intensively managed or irrigated areas (Bradford et al., 2005); our study asserted that crop species choice could switch this outcome even in the arid edge of rainfed agriculture. Certainly, maize crop with a C4 metabolism with higher photosynthetic and water use efficiency (Farquhar et al., 1989), duplicated the aerial net primary productivity of the C3 natural woody vegetation, which in turn was slightly higher or similar to that of soybean and wheat crops. Fallows transferring soil water, homogenous stands or suppression of plagues and diseases, among others agriculture interventions, as they increase resource use efficiency (Begon et al., 2009) may also overcompensate the adaptive advantages of natural vegetation (Bacon, 2004). However, if we only consider biomass residues remaining on site available for ecosystem processes and services after harvest for humans appropriation (Fisher et al., 2009), together with theoretical differences in below–aboveground structures (Gower et al., 1999), we found that only maize contributions are closer to natural woody vegetation, while soybean and wheat cut them substantially. These results support maize as a unique crop choice with an enormous potential for more sustainable land use transitions balancing food and biomass production, with boundary productivity limits that reach 200 mm of seasonal water supply and almost two times higher yields than those attained currently in our study region (Grassini et al., 2009).

In contrast with our expectations, biomass productivity in pastures did not stand out at intermediate precipitation values, being only higher than natural grasslands but outperformed by natural woody vegetation and crops even at the most arid edge. These findings could be related to several causes. First, similar to other herbaceous species, annual biomass production in pastures is highly conditioned by seasonal precipitation and the number of plants, seedlings and vegetative tillers that survives from the previous year (Sala et al., 2012). Thus, the low performance of pastures may be caused by the lack of deep roots or fallow management to ensure water availability in critical periods, and a lesser amount of persistent meristems or the lack of artificially implanted seeds to ensure the continuous density of growing buds, compared to natural woody vegetation and crops, respectively. Second, despite sharing with maize the photosynthetic and water use efficiency benefits of C4 metabolism (Farquhar et al., 1989), the standing dead tissue and the costly root systems of pastures may attenuate incident radiation and reduce aerial biomass production relative to annual crops. Finally, the unique characteristics of pastures where leaves coincide as source and sink of harvestable assimilates compromise the development of photosynthetic area and maintenance of active roots for water uptake (Ryle and Powell, 1975), thus lowering its performance in dry conditions.

In spite of being estimated with uncommon high-end achievable production schemes, pastures and then natural woody vegetation achieved a much lower comparative land-use efficiency than crops to produce harvestable products, edible energy and protein, relative to differences in biomass productivity, coincident with other reports for the same region (Grau et al., 2008; Rueda et al., 2013). This result likely stems from the superior partition of agricultural crops to usable components and their lower intermediate metabolic inefficiencies (Evans, 1996) compared to natural forest and livestock production. Particularly maize and soybean are two of the current most efficient breeded grain crops in terms of edible energy and protein production, and lower nutrient needs (Jobbágy and Sala, 2014). Additionally, genetic modifications for weed and plague suppression together with new soil and water management practices allowed late-sown crops moderating unproductive loses and stress during critical periods in dry environments (Calviño and Monzón, 2009; Giménez et al., 2014). The opposite occurs in natural vegetation and pastures where increasing aridity imply decreases in usable forest biomass fraction (Rueda et al., 2013) and forage quality (Garbulsky and Deregibus, 2004), reducing agronomic yield more than proportionally than precipitation and primary production. Aggravating this, historical regional forest degradation (Gasparri and Baldi, 2013) demands radical changes in conservation paradigms towards forestry intensification practices that promote more productive forest structure and valuable species composition (Fredericksen and Putz, 2003).

The outstanding soybean economic profits that we found agree with other reports that emphasized its central role as a regional deforestation driver (Barona et al., 2010; Gasparri et al., 2013), despite having lower primary productivity and yield performance than maize. Two factors mainly define this controversial result. First, rise in road transport costs towards less accessible remote areas discourage any other crop but soybean, whose highest price still ensure its profitability. While playing a historical key role in commodity production and agriculture expansion (Grigg, 1974), lower cost of railway or fluvial transportation could drastically counterbalance this scenario, as it would increase the relative profit of maize over soybean. Similar effect can be achieved through local industrialization of grains or animal feeding. Second, disproportionately high costs of transgenic seeds of hybrid maize (i.e. harvested seeds will not reproduce true to type) could discourage farmers adoption, opposite to soybean where autogamous reproduction and local legislation protecting farmers avoid an excessive technology fee, favoring widespread adoption (Leguizamón, 2014; Qaim and Traxler, 2005). This suggest that a potential maize seed cost reduction via technical advances, monopoly pricing regulation or subsidies, among others, could also counterbalance current soybean monoculture adoption in the studied agricultural frontiers.

Reduced gross income of cattle ranching business compared to crops is controversial as pasture expansion accounts for most regional deforestation (Clark et al., 2010; Houspanossian et al., 2016), similar to observed even in more humid agricultural frontiers in Brazil (Macedo et al., 2012) and throughout Latin America (Graesser et al., 2015). While initial irruption of pastures is favored by low logistics and transport cost of cattle for foreign ranching business, this may facilitate subsequent rise in commodity crops and land prices (Meyfroidt et al., 2014) that incentive ranchers to sell and relocate into more remote regions (Richards et al., 2014). Thus soybean cropping and cattle ranching act as coupled drivers, where often single actor operates in both sectors (Gasparri and le Polain de Waroux, 2014). In the case of local ranchers, while cultural and financial aspects may limit a rapid shift to agriculture, pastures highest return of functional capital invested may enable a gradual capital accumulation on livestock. Thus, a combined imprint of foreign and local ranchers may explain pasture relevance at the beginning of deforestation when land prices are low and functional capital is limiting, until this factors are inverted due to crop introduction (Richards et al., 2014). Pastures only outstand in driest areas without viable crop alternatives yet and where scattered vegetation allow coarse deforestation methods like roller chopping (Blanco et al., 2005).

The contrast between the strong economic incentives for agriculture and the poor performance of traditional ranching-forestry use of natural vegetation coincide with high deforestation rates observed in these and biophysically similar ecoregions of the world (Baldi and Jobbágy, 2012; Gasparri et al., 2015; Vallejos et al., 2014). To be at least equal to pastures, forestry business will need improbable improvements like tripling timber yields or doubling of prices or almost null direct operative cost. Away from compensate this, lower transport costs may drive to more deforestation, as agriculture profits increases more than proportionally and indirectly raise labor costs. Meanwhile, selective understory clearing methods has been proposed to simultaneously increase forage and timber yield (Alvarez et al., 2013; Anriquez et al., 2005; Carranza and Ledesma, 2005; Kunst et al., 2012). Controversially, these interventions may contain changes of forest landscape natural features, including its functioning and biodiversity, especially compared with agriculture (Mastrangelo and Gavin, 2012). But assuming similar management costs for pastures in the understory than in deforested plots, our analysis suggest that it will be necessary to achieve at least 70% of the forage produced with them to reach similar gross income. The solution could be the invention of low-cost mechanical biomass harvesters for selective understory clearing operations that also allow to generate electricity and prevent wildfires (Verón et al., 2012). Only improved forest economic profits may effectively reinforce the observance and permanence of recent laws that attempts to conserve >420,000 km^2 of the remaining natural forest (Vallejos et al., 2014).

Our simplified assumptions, extrapolation and performance indicators allowed comparisons across alternative perspectives and vegetation covers through broad ecoregions. However, we recognize that some methodological constrains limit the scope of our results. i) From the ecological perspective, unconsidered traits as nutrients cycling, species diversity and structure, or pesticides and transgenic organisms use, among others, may also be of a great concern. ii) Similarly, subsuming the economic perspective to the private financial dimension of large-scale commodities as present deforestation drivers (Gasparri et al., 2013; Gasparri and le Polain de Waroux, 2014; Leguizamón, 2014), impedes the recognition of its environmental liabilities and coexistence with a diverse array of land users (Baldi et al., 2015), nonmarketable benefits and alternative food systems. iii) Profits may be underestimated for specific managements, as for large-scale enterprises with high logistic facilities and prices negotiation power (Leguizamón, 2014), or farmers with low-inputs strategies to minimize dry financial risks (Connor et al., 2011). Also for mixed systems that combine livestock resilience to droughts with high agriculture profits in wet years (Sadras et al., 2003). iv) Finally, specific regional data may improve possible mismatches in modeled or extrapolated ANPP and good yields, especially for woody vegetation in temperate latitudes and of pastures in warmer ones.

5. Synthesis and conclusions

Contrary to our initial expectations, our results suggest that the sign of changes in biomass production associated with the replacement of natural vegetation by agriculture depends on crop species choice rather than aridity, with maize being the most productive cover throughout the whole precipitation gradient of the Chaco and Western Espinal. The extremely high biomass production capacity and grain yield of this crop, supported by its C4 metabolism, suggest a high potential for more sustainable land use transitions instead of current soybean monoculture predominance. However, higher soybean prices, lower technology fee in seeds prices and biological nitrogen fixation determine a greater profitability for this less productive crop, particularly towards less accessible remote areas with elevated transport costs, or with less fertile soils. Despite pastures lower biomass production and profits from the macroeconomic perspective relative to crops, they showed the highest returns on functional capital invested (i.e. gross profits to operative and amortization costs ratio, without fixed capital, infrastructure and land value). This may explain pasture relevance at the beginning of natural vegetation replacement process, when land prices are low and functional capital is limiting due to reduced profits of cattle ranching business, and their decline later on when these factors are inverted due to crop introduction. Natural vegetation use with traditional mixed cattle ranching-forestry activities, even considering unlikely improvements in timber yield or prices, had the lower performance from the agronomic and economic perspectives, challenging conservation efforts.

In a region where current deforestation rise conflicts between economic growth vs. conservation, inquiries expanding knowledge of alternative options should make honest contributions for political decisions (Pielke, 2007). In this context, our research highlights three important aspects: (i) the key role of reductions in transport costs magnifying agriculture profits but mostly defining the choice of maize vs. soybean, bringing contrasting ecological and economic consequences; (ii) the cost of seed technology limiting maize production in a similar way, suggesting that seed-pricing regulation or subsidies could be another key factor to counterbalance soybean monoculture adoption in agricultural frontiers; and finally, (iii) as government regulations struggle with surveillance limitations and increasing economic pressure of agribusiness, innovations that improve diversified complementary uses of natural vegetation may, paradoxically, be a crucial avenue to its more effective conservation. Therefore, although strong agronomic and economic incentives seems to drive the territory towards its transformation, the trajectory and sign of ecological changes associated to biomass productivity are highly dependent on crop choice and other social determinants as land vs. capital costs, infrastructure, innovations and political regulations.

Acknowledgments

This work was funded by grants from the Instituto Nacional de Tecnología Agropecuaria (INTA), Agencia Nacional de Promoción Científica y Tecnológica (PICT-2013-2973) and the Inter-American Institute for Global Change Research (IAI, CRN 3095), which is supported by the US National Science Foundation (grant GEO-1128040).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2016.08.004.

References

Ahmad, P., Ashraf, M., Younis, M., Hu, X., Kumar, A., Akram, N.A., Al-Qurainy, F., 2012. Role of transgenic plants in agriculture and biopharming. Biotechnol. Adv. 30, 524–540.

Albrieu, J., Cortés, A., Sánchez, J., 2009. El transporte de ganado bovino en la República Argentina. Centro Tecnológico de Transporte, Tránsito y Seguridad Vial, UTN. Available at: http://www.utn.edu.ar/accessed 2012.

Alexandratos, N., 1999. World food and agriculture: outlook for the medium and longer term. Proc. Natl. Acad. Sci. 96, 5908–5914.

Alvarez, J.A., Villagra, P.E., Villalba, R., Debandi, G., 2013. Effects of the pruning intensity and tree size on multi-stemmed *Prosopis flexuosa* trees in the Central Monte, Argentina. For. Ecol. Manag. 310, 857–864.

Anriquez, A., Albanesi, A., Kunst, C., Ledesma, R., López, C., Rodríguez Torresi, A., Godoy, J., 2005. Rolado de fachinales y calidad de suelos en el Chaco occidental, Argentina. Ciencia del suelo 23, 145–157.

Avila, R., Di Marco, O., Agnusdei, M., Mayoral, C., 2013. Digestibilidad de la fibra y materia seca de dos gramíneas megatérmicas (*Chloris gayana* y *Cenchrus ciliaris*) de diferente porte: Relación con la edad y largo foliar. Revista Argentina de Producción Animal 30, 1–13.

Bacon, M.A., 2004. Water Use Efficiency in Plant Biology. Blackwell.

Baldi, G., Jobbágy, E., 2012. Land use in the dry subtropics: vegetation composition and production across contrasting human contexts. J. Arid Environ. 76, 115–127.

Baldi, G., Houspanossian, J., Murray, F., Rosales, A.A., Rueda, C.V., Jobbágy, E.G., 2015. Cultivating the dry forests of South America: Diversity of land users and imprints on ecosystem functioning. J. Arid Environ. 123, 47–59.

Barona, E., Ramankutty, N., Hyman, G., Coomes, O.T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ. Res. Lett. 5, 024002.

Begon, M., Townsend, C.R., Harper, J.L., 2009. Ecology: From Individuals to Ecosystems. Wiley. com.

Blanco, L., Ferrando, C.A., Biurrun, F.N., Orionte, E.L., Namur, P., Recalde, D.J., Berone, G.D., 2005. Vegetation responses to roller chopping and buffelgrass seeding in Argentina. Rangel. Ecol. Manag. 58, 219–224.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Chang. Biol. 13, 679–706.

Bradford, J.B., Lauenroth, W.K., Burke, I.C., 2005. The impact of cropping on primary production in the US Great Plains. Ecology 86, 1863–1872.

Bucher, E., Huszar, P., 1999. Sustainable management of the Gran Chaco of South America: ecological promise and economic constraints. J. Environ. Manag. 57, 99–108.

Cabrera, A.L., 1971. Fitogeografía de la república Argentina. Bol. Soc. Argent. Bot. 14, 1–42.

Calviño, P., Monzón, J., 2009. Farming Systems of Argentina: Yield Constraints and Risk Management. Crop Physiology: Applications for Genetic Improvement and Agronomy. Elsevier Academic Press, San Diego, California, pp. 51–70.

Carcova, J., Abeledo, G., Pereira, M.L., Satorre, E., 2004. Análisis de la generación del rendimiento: crecimiento, partición y componentes. In: Satorre, H., Vence, R. (Eds.), Producción de granos. Bases funcionales para su manejo. Editorial Facultad de Agronomia. UBA, Buenos Aires, Argentina, pp. 75–95.

Carranza, C., Ledesma, M., 2005. Sistemas silvopastoriles en el Chaco Árido. IDIA XXI Forestales. INTA. Vol. 8 pp. 240–246.

Clark, M.L., Aide, T.M., Grau, H.R., Riner, G., 2010. A scalable approach to mapping annual land cover at 250 m using MODIS time series data: a case study in the Dry Chaco ecoregion of South America. Remote Sens. Environ. 114, 2816–2832.

Cocimano, M., Lange, A., Menvielle, E., 1975. Estudio sobre equivalencias ganaderas. Prod. Anim. 4, 161–190.

Connor, D.J., Loomis, R.S., Cassman, K.G., 2011. Crop Ecology: Productivity and Management in Agricultural Systems. Cambridge University Press.

Coronel de Renolfi, M., Brassiolo, M., 2008. Uso de sistemas silvopastoriles en la zona de amortiguamiento del Parque Nacional Copo. Santiago del Estero. Un análisis económico. Quebracho 69–83.

DeFries, R., Field, C., Fung, I., Collatz, G., Bounoua, L., 1999. Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. Glob. Biogeochem. Cycles 13, 803–815.

DeFries, R.S., Foley, J.A., Asner, G.P., 2004. Land-use choices: balancing human needs and ecosystem function. Front. Ecol. Environ. 2, 249–257.

DeFries, R., Asner, G.P., Foley, J., 2006. A glimpse out the window: landscapes, livelihoods, and the environment. Environ.Sci. Pol. Sustain. Dev. 48, 22–36.

Del Grosso, S., Parton, W., Stohlgren, T., Zheng, D., Bachelet, D., Prince, S., Hibbard, K., Olson, R., 2008. Global potential net primary production predicted from vegetation class, precipitation, and temperature. Ecology 89, 2117–2126.

DFPCH, 2011. Informe estadistico. Direccion de Bosques de la Provincia del Chaco Available at: http://direcciondebosques.blogspot.com.ar/(accessed 2012), p. 45.

Drewnowski, A., Popkin, B.M., 1997. The nutrition transition: new trends in the global diet. Nutr. Rev. 55, 31–43.

Dussart, E., Chirino, C., Morici, E., Peinetti, R., 2011. Reconstrucción del paisaje del caldenal pampeano en los últimos 250 años. Quebracho (Santiago del Estero) 19, 54–65.

Ellis, E.C., Klein Goldewijk, K., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. Glob. Ecol. Biogeogr. 19, 589–606.

Evans, L.T., 1996. Crop Evolution, Adaptation and Yield. Cambridge University Press.

FAO, 1983. Simple Technologies for Charcoal Making. FAO Forestry Paper. Vol. 41 154 p.

Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. Annu. Rev. Plant Biol. 40, 503–537.

Ferrando, C.A., Namur, P., Blanco, L.J., Berone, G.D., Vera, T.A., 2005. Módulo experimental de cría sobre buffel grass-pastizal natural en los llanos de la Rioja, 28 Congreso Argentino de Producción Animal. Bahía Blanca, Argentina.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653.

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.

Fredericksen, T.S., Putz, F.E., 2003. Silvicultural intensification for tropical forest conservation. Biodivers. Conserv. 12, 1445–1453.

Garbulsky, M., Deregibus, D., 2004. In: FAO (Ed.), Perfiles por País del Recurso Pastura/Forraje. FAO, Argentina.

Gasparri, N.I., Baldi, G., 2013. Regional patterns and controls of biomass in semiarid woodlands: lessons from the Northern Argentina Dry Chaco. Reg. Environ. Chang. 1–14.

Gasparri, N.I., le Polain de Waroux, Y., 2014. The coupling of South American soybean and cattle production frontiers: new challenges for conservation policy and land change science. Conserv. Lett.

Gasparri, N.I., Grau, H.R., Gutiérrez Angonese, J., 2013. Linkages between soybean and neotropical deforestation: coupling and transient decoupling dynamics in a multi-decadal analysis. Glob. Environ. Chang. 23, 1605–1614.

Gasparri, N.I., Kuemmerle, T., Meyfroidt, P., le Polain de Waroux, Y., Kreft, H., 2015. The emerging soybean production frontier in Southern Africa: conservation challenges and the role of south-south telecouplings. Conserv. Lett.

Gasson, R., 1973. Goals and values of farmers. J. Agric. Econ. 24, 521–542.

Giménez, R., Mercau, J.L., Houspanossian, J., Jobbágy, E.G., 2014. Balancing agricultural and hydrologic risk in farming systems of the Chaco plains. J. Arid Environ.

Gower, S.T., Kucharik, C.J., Norman, J.M., 1999. Direct and indirect estimation of leaf area index, f APAR, and net primary production of terrestrial ecosystems. Remote Sens. Environ. 70, 29–51.

Graesser, J., Aide, T.M., Grau, H.R., Ramankutty, N., 2015. Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. Environ. Res. Lett. 10, 034017.

Grassini, P., Yang, H., Cassman, K.G., 2009. Limits to maize productivity in Western Corn-Belt: a simulation analysis for fully irrigated and rainfed conditions. Agric. For. Meteorol. 149, 1254–1265.

Grau, H.R., Gasparri, N.I., Aide, T.M., 2008. Balancing food production and nature conservation in the Neotropical dry forests of northern Argentina. Glob. Chang. Biol. 14, 985–997.

Grigg, D.B., 1974. The Agricultural Systems of the World: An Evolutionary Approach. Cambridge University Press.

Grime, J.P., 2006. Plant Strategies, Vegetation Processes, and Ecosystem Properties. Wiley.com.

Grulke, M., Brassiolo, M., Díaz Lanes, F., Obst, K., Ortiz, G., Soto, G., Michela, J., 2007. Manual para el manejo forestal sustentable de los bosques nativos de la Provincia del Chaco. Direccion de Bosques de la Provincia del Chaco, p. 135 (Available at: http://direcciondebosques.blogspot.com.ar/(accessed 2012).

Guo, L., Gifford, R., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Chang. Biol. 8, 345–360.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc. Natl. Acad. Sci. 104, 12942–12947.

Houspanossian, J., Giménez, R., Baldi, G., Nosetto, M., 2016. Is aridity restricting deforestation and land uses in the South American Dry Chaco? J. Land Use Sci. 1–17.

INDEC, 2014. Indice de precios al consumidor nacional urbano. (Available at: http://www.indec.com.ar/(accessed 2012).

Jobbágy, E.G., Sala, O.E., 2014. The imprint of crop choice on global nutrient needs. Environ. Res. Lett. 9, 084014.

Kareiva, P., Watts, S., McDonald, R., Boucher, T., 2007. Domesticated nature: shaping landscapes and ecosystems for human welfare. Science 316, 1866–1869.

Karlin, U., Catalán, L., Coirini, R., Zapata, R., 2004. Uso y manejo sustentable de los bosques nativos del Chaco Arido. In: Arturi, M.F., Frangi, J.L., Goya, J.F. (Eds.), Ecología y manejo de bosques nativos de Argentina. Presentación multimedia. Editorial Universidad Nacional de La Plata, La Plata, pp. 1–22.

Kunst, C., Ledesma, R., Bravo, S., Albanesi, A., Anriquez, A., van Meer, H., Godoy, J., 2012. Disrupting woody steady states in the Chaco region (Argentina): responses to combined disturbance treatments. Ecol. Eng. 42, 42–53.

Laca, E.A., 2009. New approaches and tools for grazing management. Rangel. Ecol. Manag. 62, 407–417.

Lambers, H., Chapin, F.S., Pons, T.L., 1998. Plant Physiological Ecology. Springer.

Leguizamón, A., 2014. Modifying Argentina: GM soy and socio-environmental change. Geoforum 53, 149–160.

Macedo, M.N., DeFries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc. Natl. Acad. Sci. 109, 1341–1346.

Magliano, P.N., Murray, F., Baldi, G., Aurand, S., Páez, R.A., Harder, W., Jobbágy, E.G., 2015. Rainwater harvesting in Dry Chaco: regional distribution and local water balance. J. Arid Environ.

MAGyP, 2012. Estimaciones Agricolas de Cereales, Oleaginosas, Industriales, Frutales y Hortalizas, Ministerio de Agricultura Ganaderia y Pesca. Servicio Integrado de Informacion Agropecuaria (Available at: http://old.siia.gov.ar/(accessed 2012).

Margenes, Agropecuarios, 2012. Revista Margenes Agropecuarios no 277, 288, 298 and 309, years 2008–2011. (Available at: http://www.margenes.com (accessed 2012).

Mastrangelo, M.E., Gavin, M.C., 2012. Trade-offs between cattle production and bird conservation in an agricultural frontier of the Gran Chaco of Argentina. Conserv. Biol. 26, 1040–1051.

MEA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-Being: Synthesis. Island, Washington DC.

Meyfroidt, P., Carlson, K.M., Fagan, M.E., Gutiérrez-Vélez, V.H., Macedo, M.N., Curran, L.M., DeFries, R.S., Dyer, G.A., Gibbs, H.K., Lambin, E.F., 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. Environ. Res. Lett. 9, 074012.

Morris, A., Ubici, S., 1996. Range management and production on the fringe: the Caldenal, Argentina. J. Rural. Stud. 12, 413–425.

MTEySS, 2010. Resolución 7/2010. Ministerio de Trabajo Empleo y Seguridad Social de Argentina (http://infoleg.mecon.gov.ar/infolegInternet/anexos/200000-204999/204391/norma.htm (accessed 2012).

MTEySS, 2012. Resolución 90/2012. Ministerio de Trabajo Empleo y Seguridad Social de Argentina (http://infoleg.mecon.gov.ar/infolegInternet/anexos/200000-204999/204391/norma.htm (accessed 2012).

New, M., Lister, D., Hulme, M., Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Clim. Res. 21, 1–25.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annu. Rev. Ecol. Syst. 4, 25–51.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., 2001. Terrestrial ecoregions of the world: a new map of life on earth. Bioscience 51, 933–938.

Pfaff, A.S., 1999. What drives deforestation in the Brazilian Amazon?: evidence from satellite and socioeconomic data. J. Environ. Econ. Manag. 37, 26–43.

Pielke, R.A., 2007. The Honest Broker: Making Sense of Science in Policy and Politics. Cambridge Univ Press.

Qaim, M., Traxler, G., 2005. Roundup ready soybeans in Argentina: farm level and aggregate welfare effects. Agric. Econ. 32, 73–86.

Richards, P.D., Walker, R.T., Arima, E.Y., 2014. Spatially complex land change: the indirect effect of Brazil's agricultural sector on land use in Amazonia. Glob. Environ. Chang. 29, 1–9.

Rockström, J., 2004. Making the best of climatic variability: options for upgrading rainfed farming in water scarce regions. Water Sci. Technol. 49, 151–156.

Rueda, C.V., Baldi, G., Verón, S.R., Jobbágy, E.G., 2013. Apropiación humana de la producción primaria en el Chaco Seco. Ecología Austral 23, 44–54.

Rueda, C.V., Baldi, G., Gasparri, I., Jobbágy, E.G., 2015. Charcoal production in the Argentine Dry Chaco: where, how and who? Energy Sustain. Dev. 27, 46–53.

Ryle, G., Powell, C., 1975. Defoliation and regrowth in the graminaceous plant: the role of current assimilate. Ann. Bot. 39, 297–310.

Sadras, V.O., Roget, D.K., 2004. Production and environmental aspects of cropping intensification in a semiarid environment of southeastern Australia. Agron. J. 96, 236–246.

Sadras, V.c., Roget, D., Krause, M., 2003. Dynamic cropping strategies for risk management in dry-land farming systems. Agric. Syst. 76, 929–948.

Sala, O.E., Parton, W.J., Joyce, L.A., Lauenroth, W.K., 1988. Primary production of the central grassland region of the United States. Ecology 69, 40–45.

Sala, O.E., Gherardi, L.A., Reichmann, L., Jobbágy, E., Peters, D., 2012. Legacies of precipitation fluctuations on primary production: theory and data synthesis. Philos. Trans. R. Soc. B 367, 3135–3144.

Sinclair, T., de Wit, C.t., 1975. Photosynthate and nitrogen requirements for seed production by various crops. Science 189, 565–567.

Singh, L., Singh, J., 1991. Species structure, dry matter dynamics and carbon flux of a dry tropical forest in India. Ann. Bot. 68, 263–273.

Solbrig, O.T., Orians, G.H., 1977. The adaptive characteristics of desert plants: a cost/benefit analysis of photosynthesis leads to predictions about the types and distributions of desert plants. American Scientist]–>Am. Sci. 65, 412–421.

Stritzler, N.P., 2008. Producción y calidad nutritiva de especies forrajeras megatérmicas. Revista Argentina de Producción Animal 28, 165–168.

Stritzler, N.P., Petruzzi, N.P., Frasinelli, H.J., Veneciano, J.H., Ferri, C.M., Viglizzo, E.F., 2007. Variabilidad climática en la Región Semiárida Central Argentina. Adaptación tecnologıa en sistemas extensivos de producción animal. Revista Argentina de Producción Animal 27, 111–123.

Turc, C.O., Mazzucco, R.V., 1998. Caracterización de los sistemas de aprovechamiento forestal utilizados en los montes santiagueños. Quebracho 6, 59–68.

UMSEF, 2008. Monitoreo de la superficie de bosque nativo de Argentina. Secretaria de Ambiente y Desarrollo Sustentable. Buenos Aires, Argentina.

UNESCO, 1977. World Map of Arid Regions. United Nations Educational, Scientific and Cultural Organization, Paris.

USDA, 2011. USDA National Nutrient Database for Standard Reference: Release 14. USDA, Washington.

Vallejos, M., Volante, J.N., Mosciaro, M.J., Vale, L.M., Bustamante, M.L., Paruelo, J.M., 2014. Transformation dynamics of the natural cover in the Dry Chaco ecoregion: a plot level geo-database from 1976 to 2012. J. Arid Environ. in press.

Verón, S.R., Jobbágy, E.G., Di Bella, C.M., Paruelo, J.M., Jackson, R.B., 2012. Assessing the potential of wildfires as a sustainable bioenergy opportunity. GCB Bioenergy 4, 634–641.

Viglizzo, E., Lértora, F., Pordomingo, A., Bernardos, J., Roberto, Z., Del Valle, H., 2001. Ecological lessons and applications from one century of low external-input farming in the pampas of Argentina. Agric. Ecosyst. Environ. 83, 65–81.

Viglizzo, E.F., Frank, F.C., Carreño, L.V., Jobbagy, E.G., Pereyra, H., Clatt, J., Pincen, D., RICARD, M.F., 2011. Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. Glob. Chang. Biol. 17, 959–973.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., Matson, P.A., 1986. Human appropriation of the products of photosynthesis. Bioscience 36, 368–373.