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Charcoal production in the Argentine Dry Chaco: Where, how and who?

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ABSTRACT

Charcoal production has been widespread in the past and is still common where poor societies and dry forests coexist. For the Dry Chaco in South America, one of the largest remaining dry forests of the world, we describe the geographical distribution, type of production systems, environmental and social context and output of charcoal based on remote sensing (charcoal kiln detection); together with existing environmental (forest cover/biomass), social (population density, poverty), and infrastructure (roads) data. While most of the region has low kiln densities (<1 kiln every 1000 km^2), foci of higher production were found in the north of Santiago del Estero and the west of Chaco provinces (>1 kiln every 5 km^2). Individual or small groups (up to three units) prevail over the regions (58.2% of all kiln sites), frequently associated with a forest land cover. Large groups of kilns (≥12 units, 15.5% of all kilns) were associated with land cleared for cultivation. For a subset of kiln sites for which forest biomass data was available, we found that typical kiln sites (1–3 kilns) had half of the average biomass of the region within a radius of 125 m. Although charcoal production in the whole region has been stable for 50 years, a strong redistribution from richer to poorer provinces has taken place. At the county level, kiln density and charcoal production records showed a linear association that suggests an average output of 11 tons of charcoal per year per kiln. Comparing counties with high vs. low charcoal production with similarly high forest cover, the first had higher population density and poverty levels. Today small scale charcoal production by poor rural people represents the only significant use of forests products that provides some market incentive for their preservation. However this situation is associated with marginal social conditions, inefficient production, and forest degradation. Developing charcoal production under environmentally and socially virtuous conditions should be seen as a unique opportunity and an urgent challenge in the face of the fast deforestation of dry forests.

Introduction

Woody biomass has been the main energy source for humans until the advent of massive consumption of fossil hydrocarbons. Today its use prevails under contrasting socioeconomic conditions. On the one hand, it is common where natural woody ecosystems coincide with high poverty levels and a deficient generation, supply and distribution of energy, like in many countries of Sub-Saharan Africa (Chidumayo and Gumbo, 2010). On the other hand, it emerges as a good option under better economic conditions, where the substitution of fossil fuels by biomass is stimulated for electricity generation, heat and industrial needs as an attempt to reduce their climate impact and the dependence on limited imported resources (Antal and Mok, 1990; Parikka, 2004; Hillring and Trossero, 2006; Maciel, 2009; Bailis et al., 2013).The magnitude of the global woody biomass harvest for energy uses is uncertain today because of the lack of official records on firewood or charcoal production, particularly in poorer countries (Arnold and Persson, 2003; Niedertscheider et al., 2012). It is estimated that the global consumption of primary energy from woody fuels is only 7% of the total energy consumption (FAO, 2010), but this number would surpass 90% in developing countries (IEA, 2006), which harbor the majority of the global population. Also, charcoal production for poor as well as rich consumers, showed more than a 50% increase during 1989–2008 due to the investment in larger scale production systems (poor countries) and technology (affluent countries) (FAO, 2010).

Charcoal production involves the transformation of woody biomass, mainly cellulose, into amorphous carbon structures by an incomplete

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pyrolysis process which concentrates carbon, increasing the energetic content per unit of mass of the product (OLADE, 1983). Charcoal is produced by restricting the levels of oxygen and temperature, typically by controlling the supply of air during the combustion process (Sanabria, 1998). Traditional charcoal production structures include concrete/brick structures (e.g. Argentina and Brazil) and pits or wood piles coated with fine fresh plant material (e.g. Africa and Central America) (Carneiro de Miranda et al., 2013). Even today, the most primitive techniques for charcoal production prevail, resulting in very low yields and ratios of charcoal to firewood (dry weight) of 1:5 to 1:7 (Sanabria, 1998; Kambewa et al., 2007; Chidumayo and Gumbo, 2012; Maes and Verbist, 2012; Menemencioglu, 2013). Nevertheless, new technologies can improve yields raising these ratios to 1:3 (Sanabria, 1998; Antal and Mok, 1990).

Firewood harvest for charcoal production is traditionally performed by exploiting natural woody ecosystems, with sustainable harvesting practices being rarely applied. Woody biomass used for charcoal production includes materials of contrasting values, ranging from shrub species with no commercial use (e.g. Matorral in NW Mexico, Wolf and Vogel, 1986) to trees with high timber quality in N Argentina (Araujo et al., 2003). A mix of different tree and/or shrub species is usually employed (Estevez et al., 2010), and woody materials can be composed of three (e.g. Chaco woodlands in South America, Sanabria, 1998), ten (e.g. Caatinga shrublands in NE Brazil, Ramos et al., 2008) or more than thirty species (e.g. Sudanese dry forests and savannas in Africa, Kouami et al., 2009). Preference for some species and some individual plant sizes has led to selective harvesting, influencing the physiognomy and composition of ecosystems (Castillo-Santiago et al., 2012; Chidumayo and Gumbo, 2012). The aptitude of dry wood species for charcoal production is due their higher wood density compared to those from humid systems, achieving greater energetic yields, and commercial value (Briane et al., 1985; Wolf and Vogel, 1986; Antal and Mok, 1990). Also, dry forests species are less attractive for timber production given the smaller size and tortuous shape of stems, making them less attractive for uses other than firewood and charcoal. Besides traditional production under continuous forest cover, charcoal production can track pulses of deforestation, which are especially significant in drylands around the world (Portillo-Quintero and Sánchez-Azofeifa, 2010).

The geographical distribution of charcoal production not only responds to the presence of woody biomass in dry environments. Cultural and socioeconomic context has a significant importance (Ghilardi et al., 2013). In rural, densely populated, and poor conditions, charcoal production appears to be one of the few possible economic activities, requiring low capital investment and involving informal work conditions (Luoga et al., 2000; Fasano, 2010). Under these conditions, studies had often focused on biomass harvest rates and distribution, and target markets, for example, the analysis of fuel demand for charcoal production and its association with spatial patterns and the proximity to forests and cities (Arnold and Persson, 2003; Rembold et al., 2013; Zulu and Richardson, 2013; Bolognesi et al., 2015). On the other hand, studies in rich industrialized countries are focused on the sustainable use of biomass as a source of renewable energy, including charcoal. They consider forest management and use practices together with technologies for efficient fuel production (Aguilar et al., 2012; Castillo-Santiago et al., 2012; Bailis et al., 2013; Carneiro de Miranda et al., 2013).

In this paper, we explored the activity of charcoal production in the Argentine Dry Chaco. This region, still hosting one of the largest continuous areas of the dry forest of the world, has been engaged into charcoal production for more than a century and is today, based on scarce official records, its main forest product (Rueda et al., 2013). The real magnitude and geographical distribution of charcoal production in the Dry Chaco still remain uncertain. We address the following questions: (1) Where and how is charcoal produced? We specifically map the distribution of charcoal kilns and explore its association with different land covers types and conditions. (2) How much charcoal is produced? We quantify charcoal production per unit of area and per kiln. (3) Who produces charcoal? We link charcoal production rates to population and infrastructure conditions. To tackle these questions we use high resolution remote sensing imagery to locate kilns and then combine it with county level production records and other socioeconomic and environmental databases.

Materials and methods

The study area is located in the Argentine portion of the Dry Chaco region (Morello and Adámoli, 1968), which covers 480,000 km^2 in the north-central part of the country, including Salta, Formosa, Chaco, Córdoba, Catamarca, La Rioja, San Luis and Santiago del Estero provinces (Fig. 1A), and incorporating 69 counties. Original vegetation includes communities dominated by both woody (broadleaf, deciduous, or semi-deciduous trees, and shrub) and herbaceous plants (grass) (Bucher, 1982; Eva et al., 2004). Commercial forest use started at the beginning of 20th century with selective logging (Van Dam, 1996) of Quebracho Colorado (*Schinopsis quebracho-colorado*), a tree species with extremely dense wood used for railroad sleepers and tannin extraction. At the mid-century, once the railroad expansion finished, exploitation for firewood and charcoal became dominant (Red Agroforestal Chaco Argentina, 1999; Rossi, 2006). Today the Dry Chaco is still the most important native forest region of Argentina in terms of forest products, supplying 85% of the total national outputs from natural systems. The initial area of native vegetation of this region has been reduced by 20% by 2012, and its replacement by cultivated crops and pastures continues at a very fast rate (Vallejos et al., 2014). The remnant forest has likely changed as a result of grazing and selective logging, as suggested by remote sensing biomass estimates and field observations, with high evergreen trees being replaced by smaller woody plants (Gasparri and Baldi, 2013).

The databases that supported our study include natural forest production statistics for 1961–1969 (IFONA, 1969), 1980–1987 (IFONA, 1987) and 2002–2009 (PNEF, 2010). Qualitative and quantitative information on charcoal kiln distribution was obtained from very high spatial resolution imagery (VHR, 2003–2011 period) provided by the Google Earth system (www.googlearth.com). Kilns were identified by direct observation of the images based on their hemispheric shape, and a surrounding of charcoal stocking areas of a characteristic dark color of where the landscape elements used to indicate the presence of charcoal production sites (supplementary material). The geographical coordinates and the number of kilns were registered in each site. VHR scenes covered 40% of the study region and only those counties with a VHR coverage > 10% were included in this study. Road data was obtained from the "Proyecto Mapear" (2012), population data was gathered from the "Censo Nacional de Personas" (INDEC, 2010), and forest biomass information was obtained from above-ground biomass map of woodlands of Gasparri and Baldi (2013). In a subgroup of counties (Pellegrini, Copo, Alberdi and Almirante Brown) with particularly good coverage, charcoal kiln marks were classified according to their surrounding coverage which was (a) forest, (b) cleared land (including, crops and pastures) and (c) urban. Distances to roads (paved and unpaved) and to villages and towns were analyzed as determinants of kiln presence. In the case of roads, kiln density was calculated for buffer areas located at <1, 1–3, 3–5, 5–10, 10–20 and >20 km away from the nearest road. Population density was obtained from the last national census (INDEC, 2010). The analyzed variables were (i) charcoal kiln density (kilns 100 km^{-2}); (ii) grouping type and clusters of 1, 2–3, 4–6, 7–12, 12–24, >24, (iii) distance to roads (km), (iv) distance to villages and towns (km), and (v) mean aerial biomass density (tn ha^{-1}). The regional mean output was calculated at the provincial level for 1961–1969 and 1980–1987 periods, and at both provincial and county levels for 2001–2009 (tn yr^{-1}).

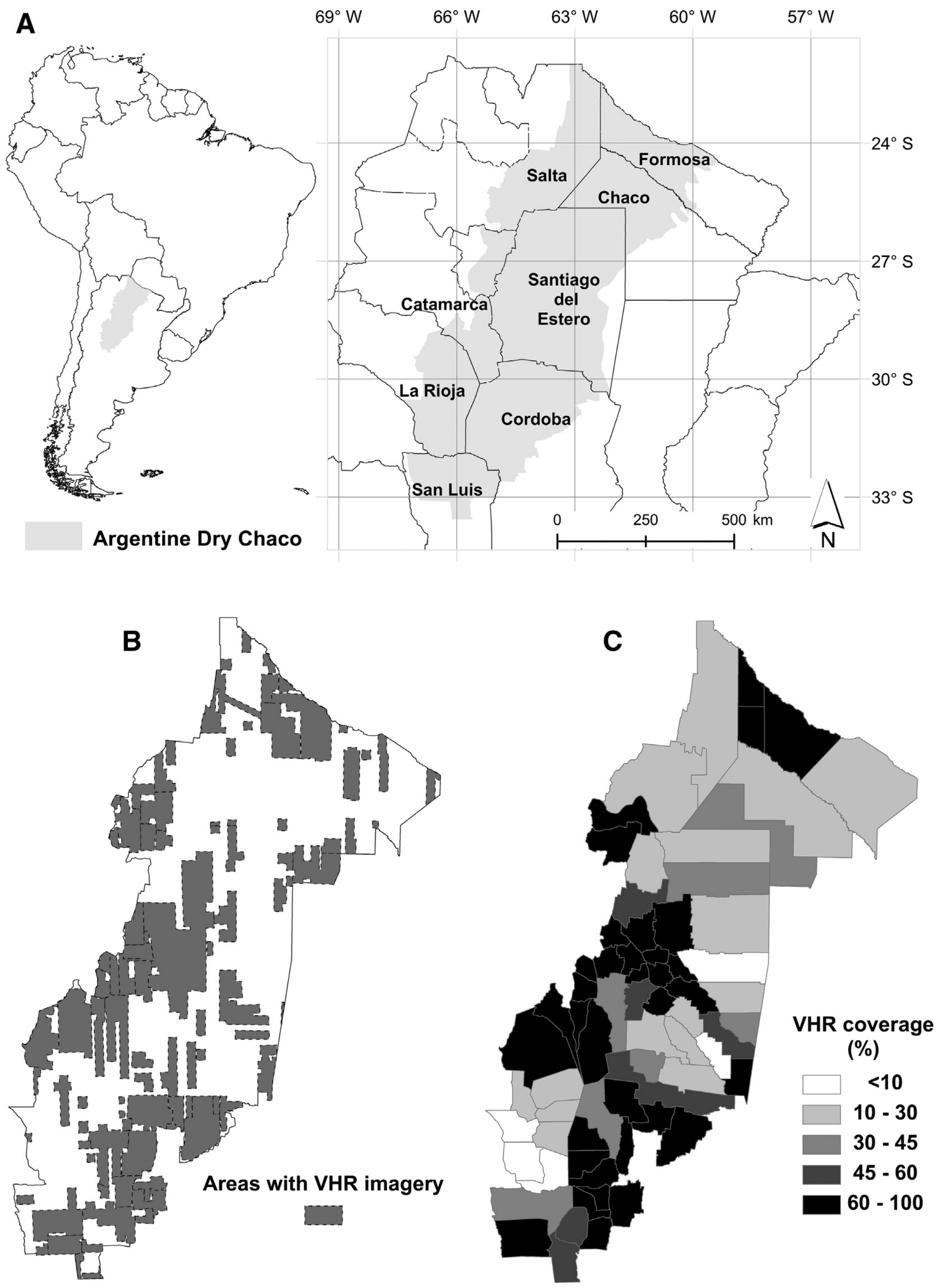

Fig. 1. A) Location of the Dry Chaco ecoregion (Olson et al., 2001) and the study area represented by 8 provinces. Coverage of satellite information and location of charcoal kilns in the Dry Chaco, (B) location of polygons in very high resolution imagery and (C) percentage of area covered in each department with high resolution images.

Results

We identified 4181 kilns in 2203 sites throughout the Dry Chaco region of Argentina after screening an area of 187,000 km^2 (40% of the territory, Fig. 1B and 1C). Kilns were concentrated in the north-center of the study region, including the west of Chaco and the north-west of Santiago del Estero provinces (achieving up to 20 kilns 100 km^{-2}, Fig. 2B and 2C). By contrast, in the southwest part of the area (La Rioja and San Luis provinces) kiln presence was nil or very rare. In terms of charcoal production, the average regional production was 3.3 tn yr^{-1} km^{-2}, but with a large spatial heterogeneity that generally copied kiln density, according to the 2002–2009 data. The highest values of production of charcoal were 575 tn km^{-2}, with more than 80% of the regional area generated < 1 ton of charcoal for every 100 km^2, making this production non-relevant in most of the territory.

Kilns were typically distributed in the form of isolated individuals or small groups (up to three spatially nearby units, 58.3% of all cases) (Table 1), and seldom in large clusters (30 sites with ≥ 12 kilns), which include however an important part of their total number (16.2% of all cases). The site with the largest group comprehended 154 kilns

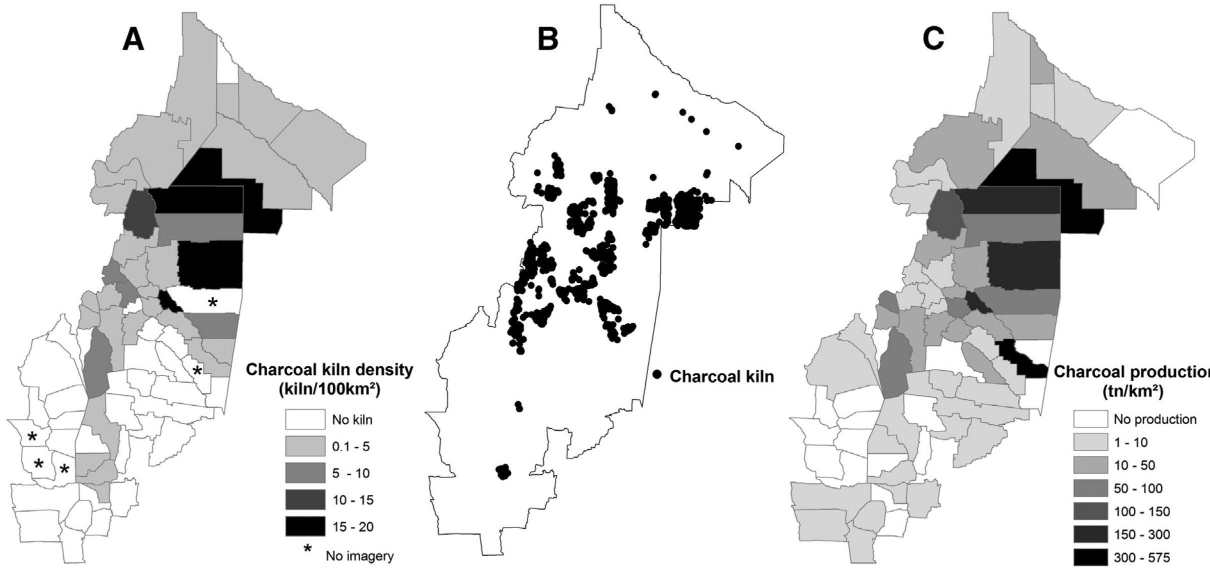

Fig. 2. A) Density of charcoal kiln for counties, B) location of charcoal kiln and C) annual average production of charcoal in the Dry Chaco counties.

in Almirante Brown county in Chaco province. In the groups of >7 kilns, it was possible to observe spatial arrangements in rows and other landscape features like stocking and truck loading areas (Fig. 3). Different grouping types were associated with each prevailing land cover. Single kilns and small groups were generally located within a forest matrix (71%), while larger groups (≥7 kilns) prevailed under cleared areas. Urban surroundings comprehend only one tenth of the sites, predominantly hosting intermediate groups of 4 to 12 kilns (Table 2).

About half of the kiln sites were located in areas with available forest biomass data. The presence of kilns implied a divergence from average forest biomass stocks (in the area of VHR imagery), and as higher the kiln density, the lower the biomass values. Sites with isolated kilns showed one half of the regional biomass stock of 110 tn ha^{-1} while for the largest groupings, biomass depletion was maximum, with complete clearing in the six sites assessed. In sites with up to 3 kilns the decline of forest biomass is not explained by forest clearing but by selective wood harvesting and forest degradation (Table 3).

According to the national records, charcoal production in the Dry Chaco region has been relatively stable since the 1960s, although producing zones have shifted their relative contribution (Fig. 4). A five-fold increase took place in the Chaco province, while a strong retraction occurred in the provinces of Formosa, San Luis and La Rioja. Total regional production in 2001–2009 was 60,000 tn yr^{-1} (Fig. 4). Increasing charcoal production in Chaco province may have been favored by a provincial law (no 5285/2003) that bans forest biomass burning following deforestation, pressing land users to allocate the harvested biomass to charcoal production or other uses.

We found a significant linear relationship between the density of kilns observed in the images and the charcoal production indicated by the national records (Fig. 5). According to the slope of this relationship each kiln would produce on average 11 tons of charcoal per year. This value can be considered as a lower boundary given that the national records are likely underestimating production and that the number of active kilns may be smaller than the total number derived from our observations. The highest value in the upper right of the plot corresponds to the department with highest total charcoal production in the Chaco province (Almirante Brown, 19.5 tn $kiln^{-1}$ yr^{-1}), Some remarkable cases in terms of disparities between observations and national statistics are the counties that have no charcoal production in records, but have kilns in our survey (most extreme case being Belgrano in Santiago del Estero). In those counties, production may remain undeclared or get recorded once it crosses their boundaries entering into another county.

Population and infrastructure conditions were associated with charcoal production in the Dry Chaco. After grouping the most productive counties (24 counties with >1 kilns 100 km^{-2}) with those displaying low or nil production (43 counties with <0.1 kilns 100 km^{-2}), we found that–although forest cover is equally high in both groups–charcoal production occurs under higher population density and poverty (Table 4). In addition, we found that where charcoal production prevails, more households use wood or charcoal for heating and cooking. Together with the broad population/demography conditions characterized at the county level, the presence of roads within forest areas played an important role defining the presence of kilns. We found that approximately one half of all the recorded kilns were located <1 km away from roads and 80% of them <5 km (Fig. 6).

Discussion

Our satellite survey of kilns, together with the national forest production records (which showed a good spatial agreement), provided the first description of charcoal production in Dry Chaco with two independent data sources. Compared to other high productive semiarid woodlands in the globe, the Dry Chaco has low kiln density even in the most productive areas (1 kiln every 5 km^2). In the woodlands of Somalia, for example, a ten-times higher charcoal productivity has been reported, considering a density of piles (piles rather than kilns are used there) of 14 per km^2 and a tentative conversion factor of 5 piles = 1 kiln (Rembold et al., 2013). These differences come with contrasting harvest methods of the forest and are likely associated with the contrasting human pressure on resources. According to our estimates, in the Dry Chaco the harvested area of a single kiln would be around 20 ha, involving the extraction of 10–20 tn of wood per hectare, and representing thus only 12.5 and 25% of the typical biomass stock of these forests (Gasparri et al., 2004). In Mozambique a single pile is

Table 1
Distribution of total charcoal kilns detected in high-resolution images by grouping type.

Grouping	Number of sites	Number of kilns	Contribution to total (%)
1	1525	1525	35.3
2–3	447	1002	23.0
4–6	139	652	15.0
7–12	52	460	10.6
12–24	19	338	7.8
>24	11	366	8.4
Total	2203	4181	100

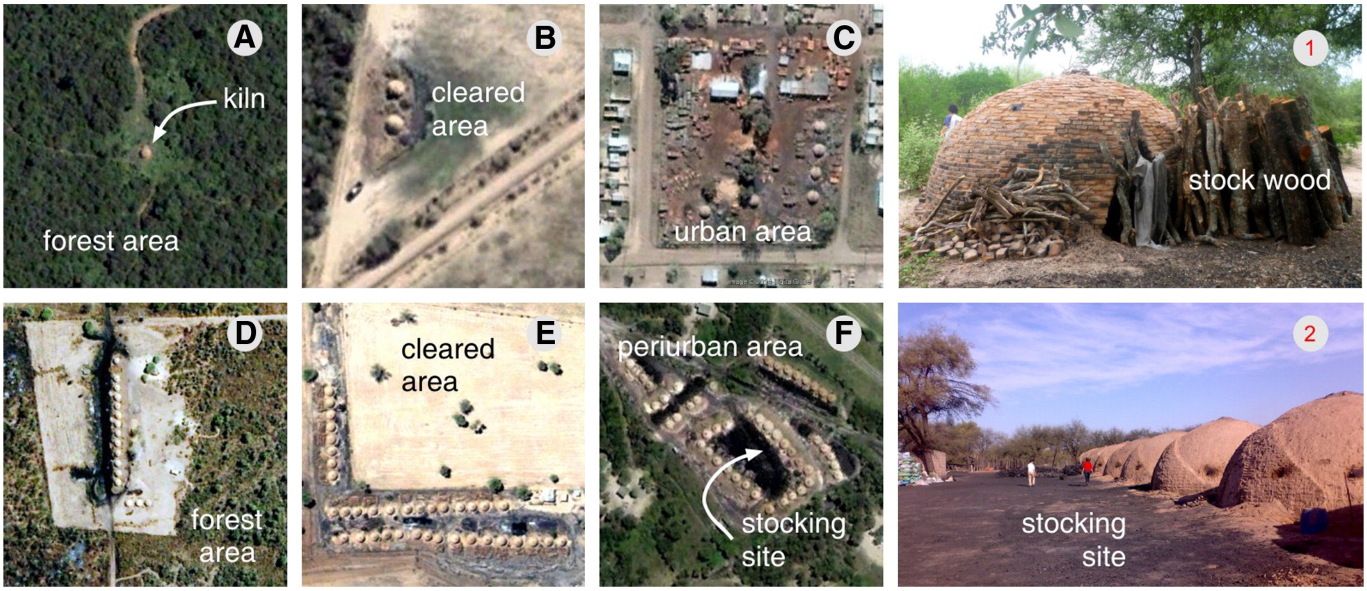

Fig. 3. Type mark according to the number of kiln and its surrounding, site with forest area (A, D), cleared area (B and E) and urban and periurban area (C and F). In (1) we showed the stock wood and (2) and (F) stocking site.

Table 2
Setting in which kilns are found in the counties of Pellegrini, Alberdi, Copo and A. Brown (14,468 km^2) according to their grouping type. Three possible settings adding up to 100% are considered: forest, including any type of woody vegetation; clearing, representing pastures, natural grasslands and croplands; and towns, involving any urban area from villages to cities.

Grouping	Forest (%)	Clearing (%)	Town (%)	Total number
1	93	6	1	868
2–3	79	12	8	403
4–6	50	18	31	222
7–12	12	53	35	182
12–24	42	42	16	86
>24	28	72	0	93
Total	71	19	10	1854

typically fed by an area of just 0.2 ha in which the totality of the woody biomass is harvested (Ryan et al., 2012). In the Dry Chaco a selective harvest of just a few species is performed (Sanabria, 1998), while in Africa charcoal production tends to involve full clearance (Chidumayo and Gumbo, 2012).

Our analysis reveals that, in terms of quantity, the largest fraction of charcoal production in the Dry Chaco takes place in small systems involving a single kiln, usually associated with natural forest cover. These systems are generally related to small-scale goat production (Red Agroforestal Chaco Argentina, 1999) and, alike the informal small charcoal producers in poor countries (Schenkel et al., 1998), correspond to the poorest segment of land users. With a smaller share of total production, large kiln groups were associated with land clearing. These last systems have possibly short production periods, performed as eventual business of farming companies (Red Agroforestal Chaco Argentina, 1999) similarly to the big errant charcoal producers described in South Africa (Schenkel et al., 1998). According to Chidumayo and Gumbo (2012), charcoal production is a primary cause of clearance and forest area shrinking in Africa. In contrast, we found in the Dry Chaco that the forest biomass is removed in order to get the land ready for agriculture, with charcoal production being only a secondary result of this activity that utilizes a small part of the biomass, most of which ends burned onsite (Verón et al., 2012).

The forest biomass stock seems to be only partially affected by kilns. The effect of full clearance, which is not driven by charcoal production, must be separated from that of selective logging for charcoal production. The stock of biomass for the forest setting with single kilns (93% of the total) (Table 2), would represent two thirds of the average biomass observed within study region according to Gasparri and Baldi (2013). This decline in biomass can be a result of logging activities, but other activities such as grazing might also have a significant impact. On the other hand, in the case of large groups of kilns, the above-ground biomass stock becomes zero. This result support the idea of large groups of kilns as a secondary activity associated with the agriculture expansion that use the forest biomass only one time during the event of land use conversion from forest to agriculture. It is not clear if after the forest conversion into agriculture these large groups of kilns are supplied with biomass from distant sources, are moved to new deforestation frontier or are just abandoned.

The limited scope of forest records hinders charcoal production quantification, not only due to the potential underestimation of outputs, but also through confused attribution of the county of origin. Figs. 1 and 2 show counties with production records but with no kilns in our study

Table 3
Aboveground biomass stock around (250 m radius) kiln locations.

Grouping	Number of marks	Number of kilns	Contribution to total (%)	Biomass (tn ha^{-1})			
				Average	Standard deviation	Maximum	Minimum
1	847	847	75.3	63	42	138	0
2–3	196	438	17.4	48	48	138	0
4–6	50	236	4.4	35	46	132	0
7–12	18	167	1.6	16	37	105	0
12–24	8	142	0.7	23	44	115	0
>24	6	180	0.5	0	0	0	0
Total	1125	2010	100				

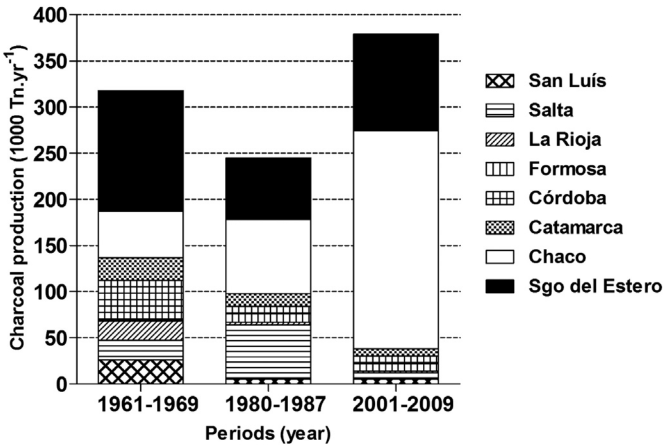

Fig. 4. Historical charcoal production by province.

(density = 0) and others with no production records but showing kilns. This would happen because of two causes: (i) counties that do not produce are used for storage/transit, and (ii) production is not recorded because it is consumed locally. In other countries this activity would have the same incomplete recording being often considered clandestine (Minten et al., 2013; Mwampamba et al., 2013a, 2013b).

The presence of both poor dwellers and roads seems to be a key condition for charcoal production in the Dry Chaco. In charcoal-producing counties poverty is higher than in the rest of the region. Which added to a higher population density suggests that charcoal is produced in those areas hosting more people under extreme poverty (according to values in Table 4, 3 vs. 1 poor inhabitants/km^2 in charcoal producing vs. non-charcoal producing counties, respectively). Simultaneous access to forests territory and roads combined with the low need for capital investment of charcoal production may push people under extreme poverty to develop this activity in the dry Chaco. Beyond the prevailing land cover, the location of kilns would be related to the interaction of the territory accessibility through roads, the population density, and the affluence level (Fig. 6 and Table 4). A condition of an accessible forest and a medium-to-high rural population density, may have pushed inhabitants of the Dry Chaco to develop a intensive charcoal production. This seems to be specially important when low affluence conditions prevail, as this activity fulfills or complements household energetic requirements while becomes a significant monetary income due to the low capital investment required (Table 4). In those regions where the domestic requirement for charcoal is higher than in ours, as in Uganda or Tanzania, the relationship between roads and kilns continues to be strong, but biomass harvest takes place on shorter distances from

Table 4
Social and demographic indicators for counties with high charcoal production (>1 kiln/100 km^2, 24 counties) and low charcoal production (<1 kiln/100 km^2, 43 counties) in the Dry Chaco. Indicators 2 to 6 show in percentages values. Urban population considers people living in towns of 2000 inhabitants. Poor households represent situations in which basic human needs are not satisfied according to records the National Censuses (INDEC, 2010).

Indicators	Charcoal-producing	Non charcoal-producing
	Average (DS)	
1—Density (inhabitants km^{-2})	12.0 (±24.8)	5.6 (±11.1)
2—Urban population	52.5 (±27.6)	45.9 (±30.7)
3—Poor households	24.9 (±9.3)	19.4 (±10.9)
4—Households using natural gas	5.2 (±12.2)	7.9 (±13.9)
5—Households using firewood or charcoal	31 (±19)	20 (±18.5)
6—Forest area fraction	92.4 (±10.7)	91.9 (±11.9)

kilns (up to 350 m on foot) (Luoga et al., 2002; Tabuti et al., 2003). When a territory has very low–or is released from–human pressure, charcoal production can be either maintained or abandoned, as suggested by regional production patterns and have relatively low pressure on harvesting the forest biomass (Rueda et al., 2013). When maintained, the destination of production changes from local to regional and national markets, making kiln location more critical due to logistic and transportation costs (Kambewa et al., 2007). Higher income levels, including access to social welfare aid, may have inclined local dwellers to abandon charcoal production, as suggested by the long term historic trends in the richest provinces of the region (Fig. 4).

Today charcoal production under single or small groups of kilns is the only existing economical system that utilizes significant amounts of biomass from the natural forests of the Dry Chaco, and the one that gives some real current market incentive for its preservation. However, this situation is associated with poverty and marginal social conditions and with inefficient production systems that yield a product that is exported of the region with little added value. Two contradictory facts about charcoal production need to be reconciled if a virtuous future for this activity is sought. On one hand, charcoal emerges as a possible approach to achieve sustainable energy supply, on the other it is an activity linked to social and economic marginality and environmental degradation. Yet, it expands in Africa and remains active in the Dry Chaco. Energy demand and the lack of other emerging commercial forest product shape a poverty circle of high impact on people and on natural resources in the poorest countries (Butz, 2013). The Dry Chaco seems to be abandoning this situation. Technological improvements (e.g. higher efficiency kilns, Bailis et al. (2013)) and policy actions could promote a "virtuous circle" of charcoal production in the region as a future alternative for fossil fuel substitution and sustainable forest development (Bailis et al., 2013; Minten et al., 2013; Mwampamba et al., 2013b).

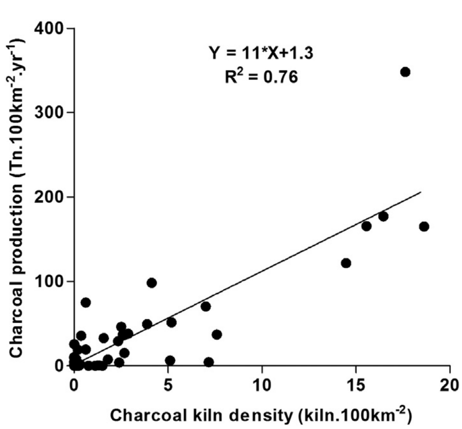

Fig. 5. Relationship between Charcoal production and charcoal kiln density for 69 counties in the study area (period 2002–2009).

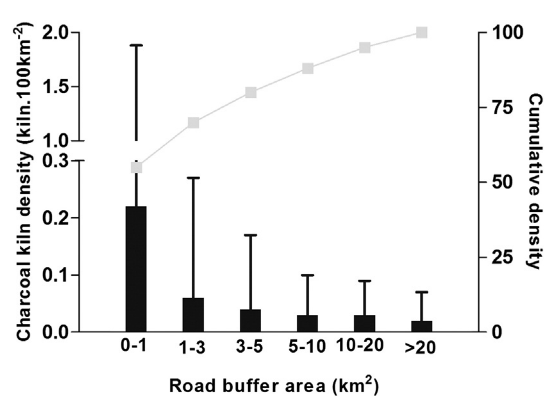

Fig. 6. Distribution of charcoal kiln density (mean and standard deviation) in function distance to road (paved and unpaved). Grey lines indicate the charcoal kiln cumulative density.

The region is still waiting for this to happen while forests are being lost at a very fast rate to give place to pastures and grain production. Developing charcoal production under more environmentally and socially virtuous conditions is a unique opportunity and an urgent challenge in the face of fast deforestation.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2015.04.006.

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