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Highlights

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Linkages between soybean and neotropical deforestation: Coupling and transient decoupling dynamics in a multi-decadal analysis

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- Soybean expansion has accompanied neotropical deforestation in recent decades.
- Brazilian soybean-deforestation decoupling is taken as an achievement of anti-deforestation policy.
- Argentine soybean-deforestation decoupling happened without anti-deforestation policy.
- Argentine and Brazilian decoupling share macroeconomic situations.
- Argentine results suggest that economic incentives overcome environmental regulation.

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Linkages between soybean and neotropical deforestation: Coupling and transient decoupling dynamics in a multi-decadal analysis

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ABSTRACT

Soybean expansion, driven by growing global meat demand, has accompanied neotropical deforestation in past decades. A recent decoupling between soybean production and deforestation in Brazil is taken as evidence of efficient deforestation regulation. Here, we assessed the relationships between soybean economy, livestock production and deforestation from 1972 to 2011 in Northern Argentina Dry Chaco. We used Panel Analysis to evaluate the relationship between soybean cultivated and deforested area in different periods and we used high resolution time series analysis of a deforestation hotspot, to explore links between soybean economy, cattle ranching and deforestation. In northern Argentina, 2.7 millions ha were deforested from 1972 to 2011, 56% of which occurred after 2002. The results of the Panel analysis indicate a strong link between soybean expansion and deforestation but with variation among periods mediated by the links between soybean and livestock productions. Deforestation was strongly coupled with soybean expansion during the 1972–1997 and 2002–2011 periods; but was largely decoupled between 1997 and 2002, when strong increments in production were accompanied by low deforestation. The high resolution analysis also indicated contrasting levels of association after and before 1997. The soybean deforestation decoupled periods in Brazil and Argentina shared similarly weak economic incentives for soybean production, rapid technological innovation and preceding high deforestation periods. In the Argentine case, when economic incentives turned positive after a 5-years decoupled period, new government measures were unable to regulate deforestation. Our study suggests that macroeconomic factors can be a much stronger deforestation force compared with domestic legal frameworks. Effectiveness of neotropical deforestation regulation should be carefully monitored and interpreted with caution paying special attention to global economic context for soybean expansion.

1. Introduction

By harboring some of the most biodiversity and biomass rich forest ecosystems, and being a major net food exporter, Latin America faces an urgent need to compromise the conservation of valuable forest ecosystems and to increase food production (Grau and Aide, 2008). A key question regarding this conservation–production compromise is weather increases in food production are achieved though increases in land use efficiency (e.g. higher yields, expansion into underutilized areas) or if instead they translate into deforestation with the resulting destruction of valuable ecosystems (Foley et al., 2011; Ramankutty and Rhemtulla, 2012).

Tropical forest was the primary source of new agriculture land in the 80s and 90s (Gibbs et al., 2010) and deforestation in Latin America during the 21st century closely accompanied exports of soybean and beef (Aide et al., 2013). This evidence suggests that, particularly in South America, deforestation has strong links with the global commodities market, and more specifically with the growing global demand of meat resulting from growing population and changing diets (Godfray et al., 2010; Kastner et al., 2012). In particular, soybean crops (mostly used for animal feed) became a major deforestation driver in Latin America (Fearnside, 2001; Grau et al., 2005; Killeen et al., 2008). However, despite the prominent role of soybean agriculture and cattle ranching on Latin America deforestation, there are few studies quantifying this link, and most of them are restricted to Brazil (e.g. Morton et al., 2006; Ewers et al., 2008; Barona et al., 2010; Macedo et al., 2012).

Studies in Brazil based on detailed remote sensing analyses of the spatial association between land uses and deforestation showed that some deforested areas were occupied with croplands, but most recently cleared land was transformed into pastures

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(Morton et al., 2006; Macedo et al., 2012). Soybean production variables were strongly correlated with deforestation rate between 2000 and 2005 (Morton et al., 2006) but this was followed by a decoupling of soybean expansion and deforestation between 2006 and 2010 (Macedo et al., 2012). Longer time series analyses did not find strong associations between the economy of soybean and annual deforestation in the Amazon (Ewers et al., 2008); and a recent, more extensive study recorded periods differing in the strength of the soybean-deforestation association (Barona et al., 2010). The recent decoupling of soybean and deforestation in Southern Amazon (Macedo et al., 2012) has been interpreted as an example of effective government measures that allowed increasing agriculture production without sacrificing forests and the biodiversity and biomass they harbor (Macedo et al., 2012; Malingreau et al., 2012). These studies provided valuable insights on the behavior of the soybean-deforestation. But they had two main limitations: (i) by being geographically restricted to Brazil, they are potentially affected by the country's idiosyncratic characteristics and this could limits its level of generality; (ii) by focusing mostly on soybean as proximate cause during short periods (5–6 years) they can only identify direct and immediate relationships (or their absence), neglecting longer term lagged or indirect associations.

To help overcoming these limitations, we analyzed the links between different agriculture and livestock productions in Argentina and deforestation of the Argentine Dry Chaco during a four-decade period. Argentina's Chaco is a rapidly expanding agriculture frontier (Clark et al., 2010; Gasparri et al., 2008) and is currently the second most active deforestation front in South America after the Amazon rainforest (Aide et al., 2013). In consequence, it provides the opportunity to explore the soybean-deforestation system under a political and socioeconomic context different from the Brazilian Amazon, but also with broad-scale ecological relevance (Viglizzo et al., 2010). Argentina is the third largest global soybean producer and exporter after USA and Brazil, and the top exporter of soybeans oil and cake (FAO, 2013). Q2 Soybean expansion has been pointed as the key driver of Argentina's deforestation (Gasparri and Grau, 2009; Zak et al., 2008) but without rigorous quantification of the association (Pincén et al., 2006; Viglizzo et al. 2010).

We designed this study with the following specific objectives: (i) to quantitatively analyze the role of soybean as driver of deforestation in Northern Argentine Dry Chaco (NADC); and (ii) to explore the coupling -decoupling soybean/deforestation dynamics during four decades in association with national socioeconomic conditions. We analyzed changes in soybean production, livestock and deforestation between 1972 and 2011, considering different spatial resolutions (region, provinces and departments); and explored temporal relationships between soybean crop economy and annual deforestation rate in NADC, including a focal analysis of hotspot of soybean expansion and deforestation (Anta sector in the Salta province).

2. Materials and methods

The Dry Chaco is the largest continuous patch of Neotropical dry forest (Portillo-Quintero and Sanchez-Azofeifa, 2010). Northern Argentina Dry Chaco (22° S–27° S and 59.5° W–65° W; Fig. 1) includes the largest share of the Argentine Chaco. The area is

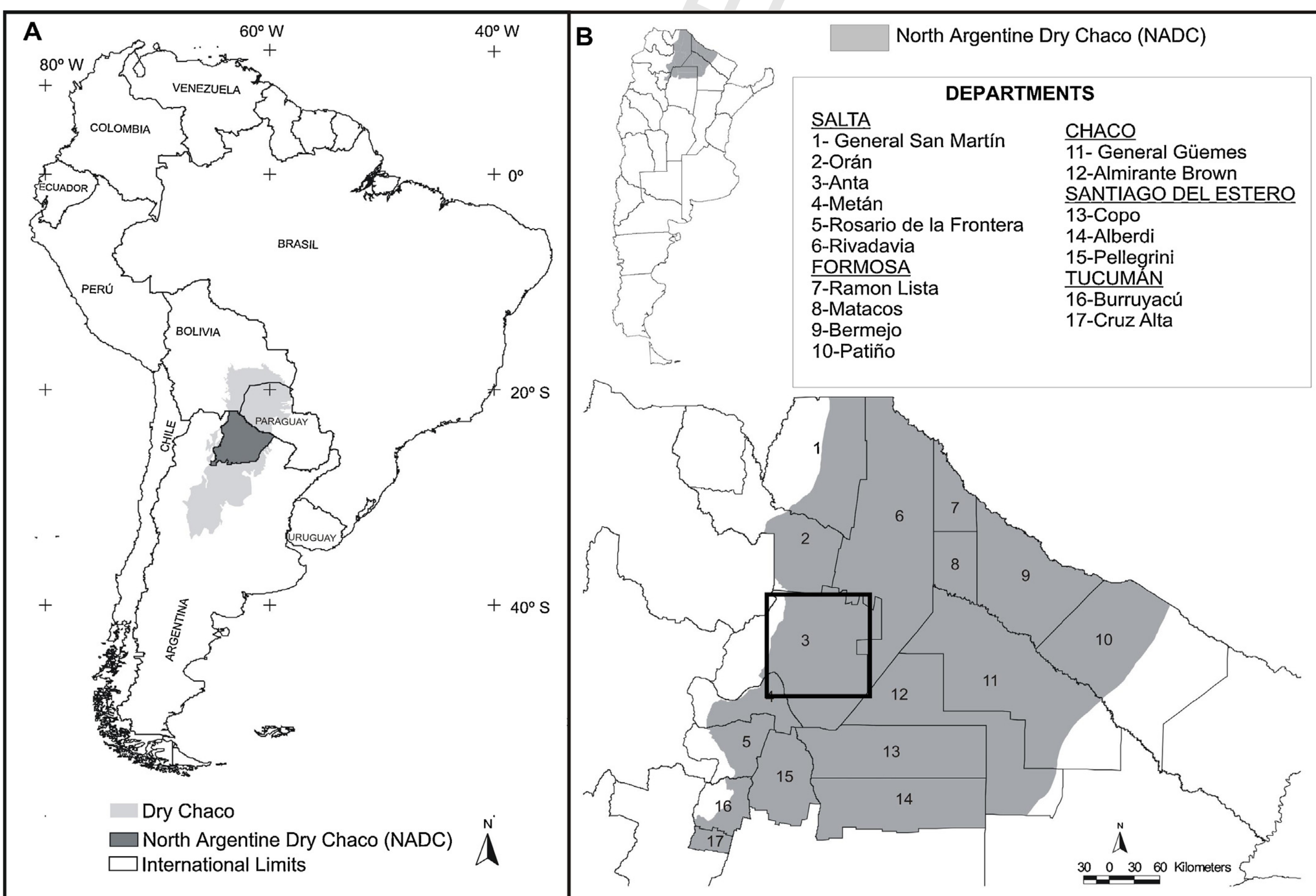

Fig. 1. Study area and departments includes in analysis for the North Argentine Dry Chaco. (A) Dry Chaco and NADC in South America. (B) References for departments in the NADC and location of the Anta sector (black-border square).

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characterized by flat relief and soils formed by aeolian and fluvial sediments. Mean annual temperature ranges between 19 and 24 °C and annual rainfall between 400 and 900 mm year^{-1}, distributed in rainy summers and dry winters, with higher values in the West and East borders of the study area (Minetti, 1999). Vegetation is dominated by broadleaf, deciduous or semi-deciduous trees and the region are considering for some authors as a neotropical broadleaf dry Forest (Gentry, 1995; Hoekstra et al., 2010).

NADC is the largest forested area in Argentina, comprehending 176,000 km^2 and 17 low-level administrative units (departments) in five provinces (Fig. 1), and including some of the most active national deforestation frontiers (Fig. 2). We mapped and estimated forests area from Landsat images of six dates: 1972, 1991, 1997, 2002, 2007 and 2011. The periods comprehended between these years are representative of different national government policies and stages of the soybean expansion history in Argentina. We combined the deforestation data in NADC with soybean statistics at different scales to explore temporal correlations, and to identify coupling–decoupling periods. To explore the links between the long time relationship of soybean expansion and deforestation we used Panel Analysis (Badi, 2008). For the Anta sector (Fig. 1) we constructed a deforestation time series from 1990 to 2008 with higher temporal resolution (1–3 years) to estimate annual deforestation. We used correlations between annual economic data of alternative deforestation drivers for the area (soybean and cattle ranch) and local deforestation to explore their proximate causal relationships.

2.1. Deforestation data

To quantify deforestation in NADC, we prepared maps by on-screen digitalization of deforested polygons between two dates based in visual interpretation of Landsat images of six approximate dates: 1972 (MSS), 1991 (TM), 1997 (TM), 2002 (TM), 2007 (ETM and TM) and 2011 (TM). The map projections system employed was the Argentine official system Gauss-Krügger – Zone 4. A list of images used in our study is showed in Tables A1 and A2. Not all the images are exactly of the years taken as reference but we

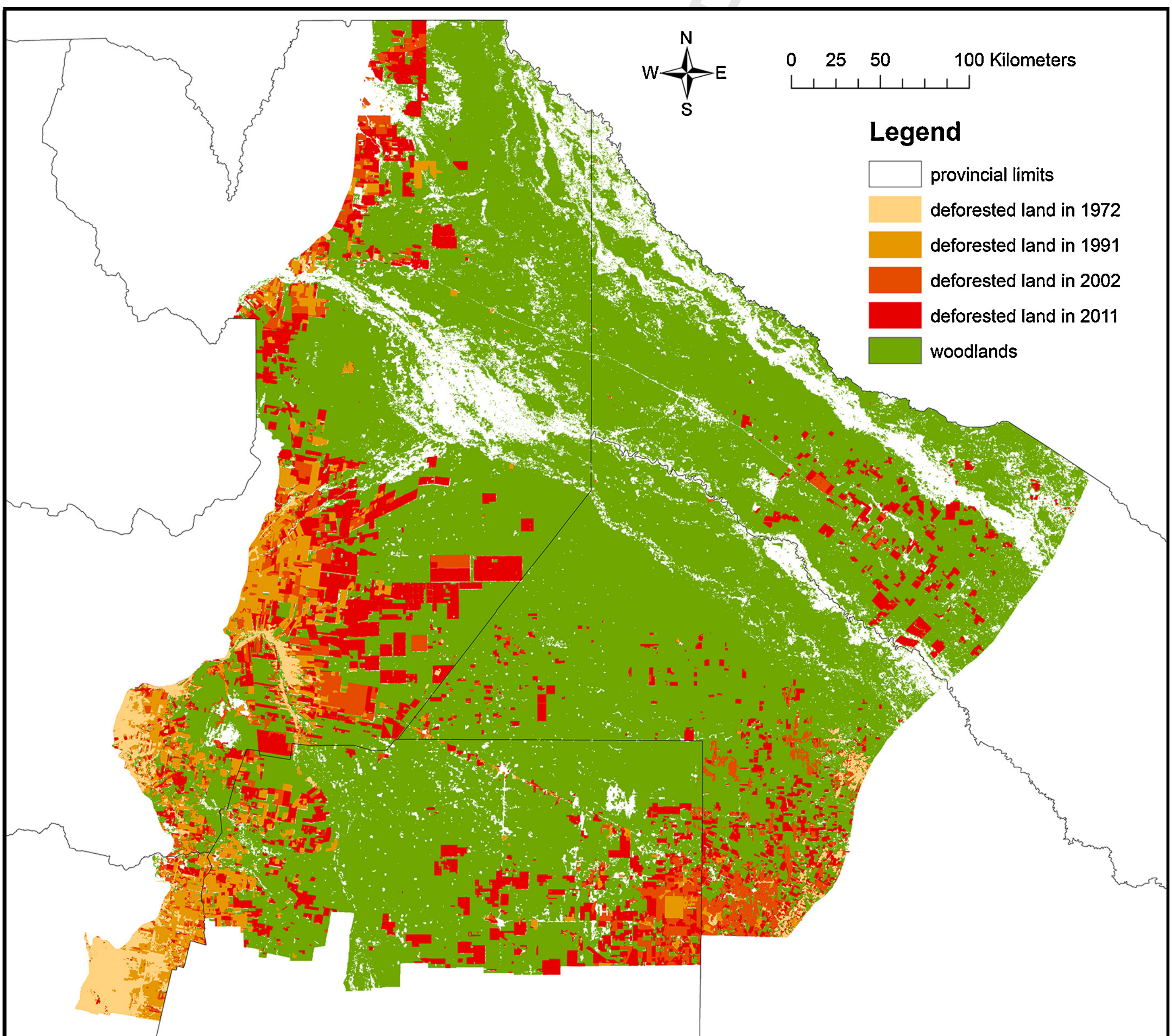

Fig. 2. Map of forest and deforested areas in NADC in different time periods between 1972 and 2012.

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determined the reference year based in the majority acquisition dates and the date of images that provide the most active sector of deforestation. We used the standard forest definition (continuous dense tree covers >20%) and procedures from the National Forests Resource Assessment Program (UMSEF, 2012) to generate binary maps of forest-no forest previously assessed with an overall exactitude of 92% (Grau et al., 2005).

For time series of deforestation in the Anta sector, we carried out a digital classification of July–August (winter/dry season) Landsat-5 TM images to produce binary maps of forest and no-forest areas (here, mainly represented by cultivated plots) from 1990 to 2010 every two or three years depending on the availability of cloud-free scenes. The Anta sector (25°10′ S 64°57′ W; 23°56′ S 62°47′ W) is included in the scene 230/77 (path/row). Scenes were obtained from INPE (Instituto Nacional de Pesquisas Espaciais, Brazil) database. Images projection (UTM 20S) and spatial resolution (30 m) were conserved as obtained from the database and co-registered with root mean square error <0.2 pixels (Table A3). Forest–non-forest maps were constructed using Random Forest Algorithm (Breiman, 2001) and Landsat bands 1, 2, 3, 4, 5 and 7. Classification was trained by selecting 306 land cover invariant pixels well spread across the scene (Fig. A1). The same points were used to generate independent classifications of each date. Jeffries-Matusita index of classes spectral separability was 1.65 (Table A3) (above 1.5 is considered acceptable; Richards and Xiuping, 2006). Digital classification of Landsat images for the Anta sector were performed with Random Forest package (Liaw and Wiener, 2002) in the R statistical software (R Development Core Team, 2012), setting 1000 trees and 3 variables per node. Overall accuracy of final maps, as evaluated by the "out-of-bag" (OOB) (Breiman, 2001) ranged from 94 to 98% for all the dates considering for the Anta sector (Table A4). Annual deforestation rate was defined as the number of forest hectares reduced between two successive images divided by the number of years (1–3) (Table A4).

2.2. Data analysis

For the analysis in NADC, we used official data of soybean cultivated area by country and by department from the official agriculture statistics of Argentina (SIIA, 2012). We described the country cultivated area of the four main crops in Argentina (soybean, maize, wheat and sunflower) as well as the Argentine official statistics on livestock for NADC. Soybean production and cattle stocks data were used in combination to deforested area for years 1972, 1991, 1997, 2002, 2007 and 2011 obtained by visual interpretation of Landsat images for the entire NADC.

To explore the role of soybean as driver of NADC deforestation we used Panel Analysis (Badi, 2008) to fit a regression between the soybean cultivated area (as independent variable) and deforested area (as dependent variable). In the PA we use data for each department ($n = 17$) in every year ($n = 6$). We performed the PA under the models of fixed-effect and random-effect; and we used the Hausman's test to select the most adequate model (Badi, 2008). All the PAs were performed in the R statistical software (R Development Core Team, 2012) with the plm package (Croissant and Millo, 2008). Additionally, for each department, we run the Pearson correlation between soybean cultivated area and deforested area in each date ($n = 6$) and for the soybean expansion rate and deforestation rate (ha year^{-1}) for each period ($n = 5$).

Finally to explore the relationship between deforestation in NADC and the whole agriculture sector of Argentina we run regressions using deforested area in NADC at each year as dependent variable and the cultivated area of main crops (soybean; wheat; maize and sunflower) of Argentina as independent variable. This analysis, considering the national soybean area and the multi annual regional deforestation rates, provides an index of the long term association between soybean and NADC deforestation which averages-out inter annual fluctuations, and short term time delays.

To quantitatively describe the coupling–decoupling dynamics between the soybean expansion and NADC deforestation, we computed two indices of the "deforestation cost" of the soybean production growth: (i) "deforestation transfer ratio by area" (DTRA), the number hectares deforested by each additional soybean cultivated hectare; and (ii) "deforestation transfer ratio by production" (DTRP), the number hectares deforested by each additional ton of soybean produced. DTRA $\geq$ 1, implies that soybean expansion is stimulating deforestation beyond the area for actual soybean cultivation, whereas DTRA < 1 would imply that soybean is expanding over other non-forest areas, and is not significantly displacing other clearing activities into forests. Small values of DTRC indicate that soybean production increases are due to expansion into non-forest areas and to increases in yield, rather than to expansion into forests. The deforestation data for the NADC estimated form visual interpretation of Landsat Images was used in combination with soybean production data to calculate DTRA and DTRP. Difference in production between years (i.e. 1972, 1991, 1997, 2002, 2007 and 2011) was estimated discriminating increases derived from area expansion and from yield increase.

To assess the immediate role of soybean as proximate cause of deforestation and its influence in short time deforestation variation, we performed a detailed analysis in one of the best known deforestation hot-spots in NADC: the Anta sector (Grau et al., 2005; Gasparri and Grau, 2009). We used the deforestation time series for the Anta sector with soybean net incomes and steer price to explore time relationship (Table A5). Annual deforestation rate was based on binary (forest–no forest) maps for Anta sector described in Section 2.1. These classifications have time steps of one to three years assuming the annual deforestation was stable within periods (i.e. annual rate was computed as the average for the period). To deepen into causal mechanisms, for this analysis we analyzed the net revenue per hectare of cultivated soybean, computed on the basis of per-hectare yields, soybean price received by the producer by ton, direct and indirect costs, and taxes. The net revenue per hectare of the soybean crop was obtained from the national statistics of the Agriculture Ministry of Argentina (SIIA, 2012), which summarizes economic descriptors of an average Argentina production of soybean from 1989 to 2006 (Table A5). We corrected the net revenue calculated with national average data by the yield in the Anta sector (corrected net revenues = national net revenues × Anta yield/national yield) to capture climatic variation in the Anta sector that could affect yield and revenues. We also described changes in steer price to assess the association between livestock production and deforestation. We used forest maps from digital classification to generate annual deforestation rate in Anta sector from 1990 to 2007 to obtain a time series that extends along the period with *quasi*-annual resolution. The time series (Table A5) of soybean per-hectare net revenue; annual average steer price and annual deforestation were used to compute one-year-lagged correlation coefficients (net revenue of year n vs deforestation rate for year $(n + 1)$) for the complete period and also allowed applying a seven-years moving window to explore variations in the association for different periods. Soybean economic and steer price data were obtained from official statistics (SIIA, 2012).

3. Results

3.1. Soybean as driver of deforestation in NADC

Between 1972 and 2011, deforested area in NADC increased from 0.3 million ha to 3 million ha (Fig. 2; Table A6). Average

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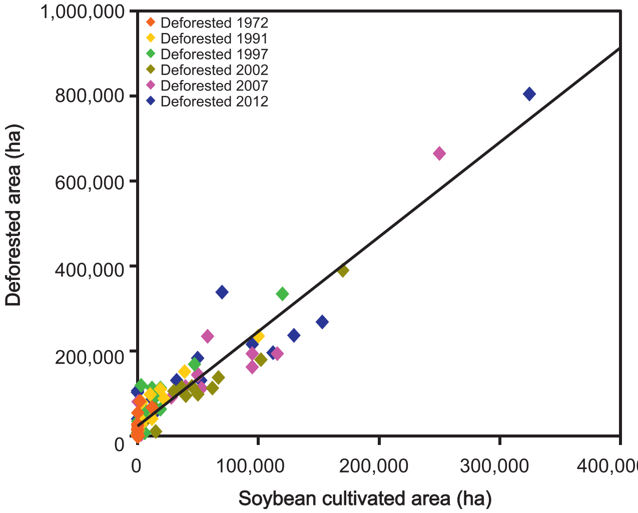

Fig. 3. Deforested area vs soybean cultivated area. Dots represent data for each department included in the NADC area ($n = 17$) at each year ($n = 6$; represented with different colors). Line represent the model fitted y derived from the Panel Analysis: Deforested area (department) = 25,064 + 2.17 × soybean cultivated area (department). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

annual deforestation rates increased during the study period, from 32,554 ha year^{-1} for 1972–1991 to 58,415 ha year^{-1} for 1991–1997; 45,659 ha year^{-1} for 1997–2002, 150,187 ha year^{-1} for 2002–2007, and 193,295 ha year^{-1} for 2007–2011. Government statistics show a constant rise of the soybean cultivated area in Argentina, from 0.01 million ha in 1972 to more than 18 million ha in 2011 (Table A7), and a similar trend in NADC (Table A8). The Panel Analysis using data of departments-by-period ($n = 102$) indicate that the soybean cultivated area has a strong long term association with deforestation (Fig. 3). The Hausman's test indicate that the Panel Analysis under the random model was the most adequate, resulting in the following model: deforested area (department) = 25064 + 2.17 × soybean cultivated area (department) ($F = 672$; $p < 0.001$; adjusted $R^2 = 0.853$).

The correlation between deforested area and soybean cultivated area using the six dates for each department varied (Fig. A2). Eleven of the 17 departments showed strong correlations ($R^2 > 0.68$) suggesting soybean is a main deforestation driver in the departments located in the west, south and southeast borders of the study area. The other six departments showed weak correlations ($R^2 < 0.2$), and in the case of the four departments of the Formosa province, these correlations were negative and non-significant. The expansion rate of soybean cultivated area and the deforestation rate by period calculated with data of each department, had correlation coefficients between 0.6 and 0.9.

Regression between deforested area in NADC and country cultivated area showed that despite more than 80% of the soybean in Argentina is cultivated outside the study area (i.e. in the Pampas), national-scale soybean area was strongly correlated with NADC deforested area ($R^2 = 0.923$; Fig. 4), indicating strong links between the core agriculture area of Argentina and the frontier agriculture in the north. In contrast, national cultivated area of others main crops (wheat, maize and sunflower) did not correlate with NADC deforestation (Fig. 4).

In the long run, trends in livestock production in NADC were also correlated in time with deforested area in NADC. But, in contrast to the steady increase in soybean area, it shows a stepwise pattern: prior to 2002 regional livestock was negatively correlated with deforestation and slowly decreasing around 5 million, but this trend reversed to grow by c. 40% to c. 7 million by the end of the decade (Fig. A3).

3.2. Coupling–decoupling periods of soybean expansion and deforestation in NADC

While soybean production expanded continuously during the 39 years of analysis (Table A7), deforestation not always accompanied the expansion, and in some periods was largely decoupled; with varying values of DTRA and DTRP (Fig. 5 and Table 1). Between 1972 and 1991 NADC was characterized by contrasting periods with incentives and dis-incentives for export-oriented agriculture (Barsky and Dávila, 2008; Gasparri and Grau, 2009). The soybean expansion occurred simultaneously with the expansion of pastures and others crops (e.g. cereals, black beans; Grau et al., 2005). As a result, c. 3 ha (DTRA) were deforested for each new soybean hectare in the region.

The period 1991–1997 was characterized by national economic growth and economic stability, and a fixed exchange ratio that

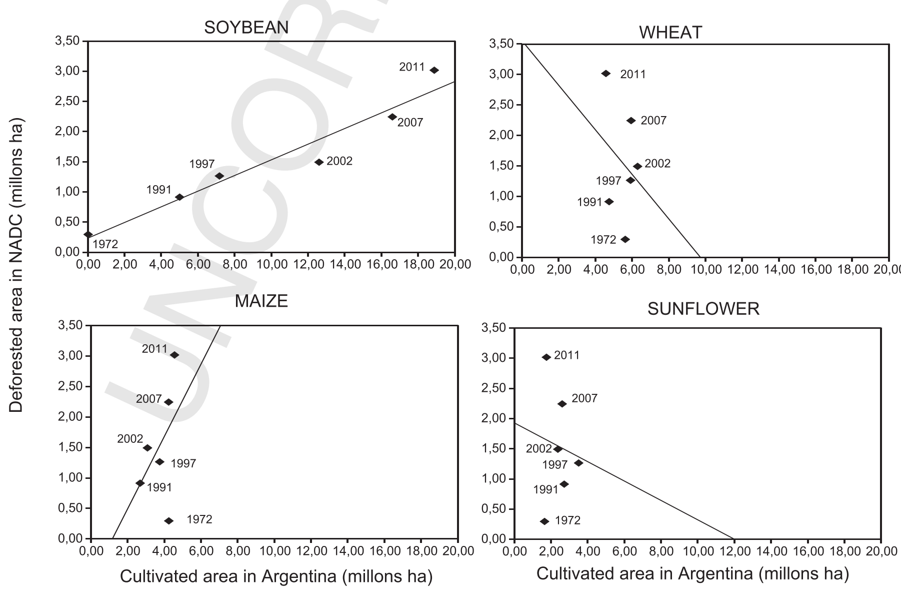

Fig. 4. Cultivated area in Argentina four main crops and deforested area in the North Argentinean Dry Chaco (NADC). Dots represent data at different years and lines represent the tendency defined by a lineal regression.

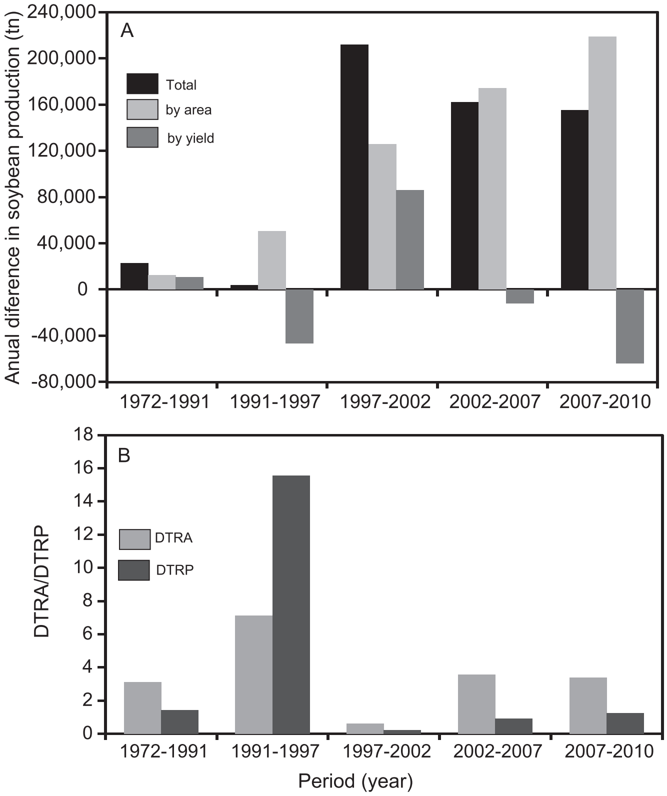

Fig. 5. (A) Differences in soybean production in the NADC for the beginning and ending year of each period calculated as annual change; (B) deforestation transfer ratio by area (DTRA) calculated as deforested area by one ha of soybean expansion; deforestation transfer ratio by production (DTRP) calculated as the deforested area by ton of soybean production increment.

derived in over-valuation of the Argentine peso, which gradually reduced Argentine competitive capacity in international markets. At the end of the period (1995 and 1996) the area experienced a severe dry period associated with La Niña (Minetti et al., 2004) with comparatively low yields and profits (see net incomes in Fig. 6 and Table A5) which resulted in high DTRP values and DTRA values of almost seven ha deforested per ha of soybean expansion.

In 1997 Argentina started a process of rapid adoption of herbicide-resistant transgenic cultivars, and between 1997 and 2002 large increases in soybean production were not accompanied by deforestation. DTRA dropped to 0.6 and increments in yield resulted in a reduction of DTRP to 0.2 ha tn^{-1}. Soybean production in NADC experienced the highest increase of the four decades considered in our analysis (220% in four years) (Fig. 5 and Table A7), and the very low values of DTRP and DTRA indicate that such increases resulted mostly from gains in yields and from expansion over already deforested areas used for others crops or pastures, rather than from new deforestation (Fig. 5).

The Argentine de-coupling, however, was not going to last (Fig. 5) and DTRA and DTRP values increased strongly between 2002 and 2011 (Fig. 5). After 2002 a new technological and organizational scheme based in transgenic cultivars of soybean was established, and the macroeconomic situations changed drastically. A 350% peso devaluation followed the 2001–2002 national economic crisis coinciding with rapid increases in global soybean prices, which provided strong incentives for soybean exports. Deforested land available for soybean expansion had become scarce again, and soybean expansion became strongly coupled with deforestation, with high production increments and very high deforestation rates (Fig. 5). DTRA jumped again to four deforested hectares per hectare of soybean expansion. This new coupling period occurred in spite of a context of some unfavorable government policies for soybean expansion and deforestation including high export taxes (*retenciones*) that were increased to a record 35% in 2008 (Barsky and Dávila, 2008) and a new national forest law, passed in 2007 and implemented in 2009 (Boletin Oficial, 2009) that prohibited new deforestation authorization for several years and established zonation maps in which deforestation was not allowed in extensive areas.

The Soybean economy and deforestation short-time dynamic analysis in the sector Anta, also shows patterns of coupling and decoupling (Table 1). Deforestation progressed steadily during the 20 years of analysis (Fig. A4 and Table A5). Along the series, deforestation was well correlated with the net income from soybean cultivation during the previous year (r = 0.723; Fig. 6A) showing that better economic performance of soybean crop is associated with higher deforestation in the following year. During the 1990s deforestation rate in Anta was partially correlated with the soybean economy but also (and with higher correlations coefficients) with livestock production (evaluated by the steer price). The correlation between soybean incomes and deforestation decreased gradually during the 1990s accompanying the decrease in soybean international prices and the fall in agriculture

Table 1
Political and economic characterization, and patterns of land use variables during the coupling/decoupling periods in northern Argentina dry Chaco between.

		Period		
		Before 1997 Coupling	1997–2002 Decoupling	2002–2011 Coupling
Characterization	Macroeconomy effect over soybean production	Neutral. Alternancy of incentives and disincentives. Strong national economy fluctuations	Unfavorable. National economy recession and over-valuation of national currency	Highly favorable. National economy recovery and devaluation of national currency. Very high international soybean prices
	Soybean economy	Unfavorable by decreasing prices and low yield because dry period	Favorable by technology change that reduced costs and increased yield	Favorable by prices increase and cost reduction due to national currency devaluation
	Deforestation regulation policy	No	No	Yes
Patterns	Deforestation	Intermediate	Low	High
	DTRA and DTRB	Intermediate–high	Low	Intermediate
	Association (correlation) between soybean economy and deforestation rate ("coupling")	Intermediate. Influence shared with livestock production	Weak	Strong

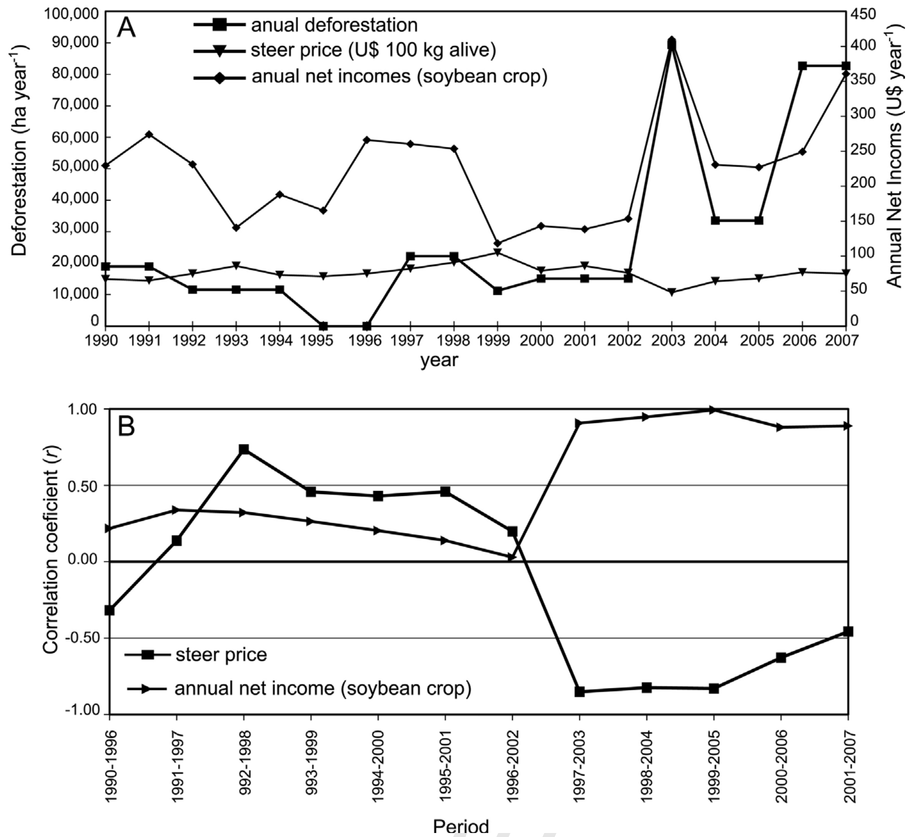

Fig. 6. (A) Annual deforestation in Anta sector and annual net incomes for a soybean crop adjusted for Anta. The net income of soybean production was draw with a time lag of 1 year. (B) Correlation coefficient over time between deforestation and the net annual income of soybean adjusted for Anta and the steel price. Correlation coefficient was calculated for seven-year moving windows.

production in 1995 and 1996 resulting from the regional drought (Minetti et al., 2004). However, in 1997 the situation shifted markedly (Fig. 6B); the correlation between soybean income and deforestation in the period 1997–2005 jumped to much higher values (>0.8) (Fig. 6B) while the correlation between steer price and deforestation fell (Fig. 6B).

4. Discussion

4.1. Soybean as driver of deforestation

In response to changes in overall consumption and diet (Godfray et al., 2010; Kastner et al., 2012), agriculture production ultimately aimed to supply global meat demand, is growing globally. In South America, the rate of soybean and meat exports closely followed deforestation rates during the 21st century and the two countries experiencing the fastest deforestation rates are Brazil and Argentina (Aide et al., 2013). Consistently with previous analyses (Pincén et al., 2006) our results indicate that soybean expansion in Argentina correlates with deforestation rate at different administrative levels and geographic scale, thus soybean cultivation can be considered the main deforestation driver for the NADC as has been found in Brazil (Barona et al., 2010; Ewers et al., 2008; Morton et al., 2006). Soybean expansion is a very strong predictor of deforestation at extensive geographic scales and long time periods, as well as in the short term analysis in the Anta sector (a local "hotspot" of Chaco deforestation).

The central role of the soybean expansion as deforestation driver in Argentina has been objected by some authors who consider soybean in a similar influential level as other crops (Barsky and Dávila, 2008; Viglizzo, 2011) partly based on observations of other post-deforestation land uses. The regional effect of soybean activity on deforestation, however, is not limited to the fine-scale proximate effect on each particular plot; but, most importantly, to the overall economic effect on agriculture activity, including indirect and time-delayed effects such as displacement of livestock and other crops to suboptimal agriculture areas (Arima et al., 2011; Goldfarb, 2012). On average, per each new hectare of soybean, 2.17 ha (Panel Analysis coefficient) were deforested in NADC during the whole study period, implying the other non-soybean land uses represent more than half of the post-deforestation use. In particular, forest clearing to plant pastures (mainly *Panicum maximum* cv. *Gatton panic*) appears to be an alternative deforestation pathway, but this could also be indirectly connected with dominant soybean-driven agriculture activity. Furthermore, our short term analysis for the Anta sector suggests a subordinated role of cattle activity to the economy of the soybean during the 2000s; and we argue that post-deforestation uses may be a poor index of deforestation driving forces. Between 2001 and 2010, our index of livestock economy (steer price) showed little association with the deforestation rate, despite much of the recently deforested plots were cultivated with pastures (Clark et al., 2010). Strong correlation between soybean economy and deforestation during this period suggests that these plots were deforested with capitals from soybean activity although they were immediately used for cattle grazing.

Our analysis opens some questions about the influences of cattle ranching and pastures on deforestation and its relationship with agriculture. Livestock production and pastures are typically considered as an alternative use competing for land with agriculture (Morton et al., 2006). Our data suggest a more complex

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interaction. For the NADC case, we hypothesize that cattle ranching and soybeans agriculture are part of the same system or "complex" of drivers. Cattle ranching fluctuated as an alternative production activity (until 1997) to become a subordinated activity largely based on capital inflows from extraordinary revenues of the soybean (2002–2011). In both cases, cattle ranching and related pastures plantations could be acting as mediators of soybean-driven deforestation. Pastures could (with soybean originated capital) be creating deforested land reserves to be later used for soybean. This synergistic role of pastures and soybean could explain the decoupling periods of Argentine and Brazil (Macedo et al., 2012) and need more attention and empirical studies (e.g. analyzing in detail the capital and decision flows between livestock production and soybean activities).

4.2. Coupling–decoupling periods of soybean production and deforestation

As said, the main driver of deforestation in NADC is soybean expansion. However, the relationship between the soybean as cause of deforestation changed through time and this is reflected in fluctuating values of DTRA and DTRP (Fig. 5) and in the varying relationship between soybean economy and short-time deforestation dynamic of the Anta sector (Fig. 6). The way soybean operates as a deforestation driver can be discriminated in three periods, respectively of moderate coupling (pre 1997), de-coupling (1997–2002), and reinforced high coupling (2002–2010) between the two variables (Table 1).

In our analysis for the Argentina case, the "decoupling" process was not the result of any particular government land use policy, regulation or intervention. Instead, is likely that low capital availability (due to domestic economic recession and low international prices) limited resources for investments in deforestation, and high Peso-Dollar exchange ratio re-directed these limited financial resources to acquisition of high-capital imported technology rather than to land acquisition or forest removal. Investments in technology coupled with the adoption of transgenic cultivars and water-efficient non-tillage associated practices, resulted in a reduction of production costs and better agronomic performance in dry areas (Grau et al., 2005). Areas under-used or planted with pastures in the previous period (due to fast deforestation and a severe drought that limited agriculture expansion into suboptimal climatic zones) allowed soybean expansion without deforestation; similar to what has been observed in Brazil's recent decoupling process (Macedo et al., 2012).

The short-time deforestation dynamics of the Anta sector, also reflect the coupling/decoupling patterns in the moving window correlation analysis (Fig. 6B). During the 1990s deforestation rate in Anta was partially correlated to the soybean economy but also with livestock production (evaluated by the steer price); this correlation decreased gradually during the 1990s accompanying the decrease in soybean international prices and the fall in agriculture production in 1995 and 1996 resulting from the regional drought (Minetti et al., 2004). The introduction in Argentina of soybean transgenic cultivars (in 1997) and major macroeconomic changes occurred after 2001 implying strong incentives for the export-oriented agriculture sector In contrast, cattle production of Argentina was affected by a reduction of international demand for red meat originated in by the Bovine Spongiform Encephalopathy ("mad cow disease"; Barsky and Gelman, 2001) and remained linked to the domestic market with a depressed demand and heavy restrictions to exports (Barsky and Dávila, 2008). As consequence, the economy of livestock production lost its effect over the deforestation dynamic.

The moving window correlation (Fig. 6B) for the post devaluation period shows that the re-coupling period of soybean expansion and deforestation was simultaneous with an increase in the effect of the soybean economy over the deforestation interannual variability; suggesting that, after national currency devaluation, extraordinary incomes from the soybean were partially used in the following years to finance deforestation operations. Exchange rates have been suggested as a relevant factor to explain deforestation patterns in South America. The Real (Brazilian currency) valuation and the international depreciation of the dollar in the last years of the 2000s (US federal funds rate near to zero) were suggested as explanation for the deforestation decline in Brazil (Richards et al., 2012). For the Argentina case, the devaluation of the Peso in 2001 clearly triggered the deforestation rebound and the soybean deforestation coupled dynamics during the following decade.

The 1997–2011 decoupling of soybean and deforestation in Argentina shares important similarities with the similar process documented for Brazil a decade later (Macedo et al., 2012). In Brazil, soybean transgenic cultivars were authorized in Brazil in 2004 demanding technological and organizational adaptation. This technological change followed a period of high deforestation rates (around 1 million ha year^{-1} from 2001 to 2005) mainly used by pastures (Macedo et al., 2012). Net incomes from soybean production were reduced by increasing transport costs, some financial restrictions as different banks adopted policies to discourage deforestation-related investments (Macedo et al., 2012), and the Real gradual appreciation relative to the US dollar (Malingreau et al., 2012; Richards et al., 2012). As in the late 1990s in NADC, during the 2006–2010 period the Brazilian state of Mato Grosso faced moderate economic incentives to soybean expansion, simultaneous with opportunities for technological adoption and large reserve of previously deforested land devoted to pastures. In contrast to the Argentine decoupling in the late 1990s, Brazil did implement government policies to control deforestation during the post 2006 period, and the analysis of this process (Macedo et al., 2012) focused on this governance aspect as the main explanation for the decoupling pattern.

But, in the Argentine case, rising export taxes during the 2000s, conflictive political situation for agriculture since 2008, and new forest protection laws did not compensate for the strong macroeconomic incentives for soybean expansion and they were overwhelmed by the very favorable macroeconomic context for soybean production, which resulted in massive deforestation, with magnitude similar to the annual deforestation in Mato Grosso (Aide et al., 2013; Macedo et al., 2012). Our example from Argentina suggests that macroeconomic conditions during a period of technological change may be important in explaining the "decoupling" process, and that deforestation government control may not be effective if macroeconomic conditions become more favorable for deforestation. Recent reports indicate an early detection of a rebound of Brazilian deforestation (Malingreau et al., 2012). This possibility needs to be seriously considered in Amazon, specially with the current Real devaluation tendency (next to 10% in first half of 2013). Changing technological and macroeconomic context for Brazil will provide the real test for the efficiency of Brazilian policies to control deforestation.

5. Conclusions

Deforestation of subtropical Chaco in Argentina has accelerated steadily during the last 40 years. Our analyses confirmed that NADC is one of the most active global deforestation frontiers of the 21st century consistently with previous works (Aide et al., 2013;

Clark et al., 2010; Gasparri et al., 2008). The main driver of this deforestation is soybean agriculture, which in NADC had a significant effect since its original introduction in the region in the early 1970s. However, the relationship between the soybean cultivated area and deforestation changed through time.

Our results about periods of coupling/decoupling between soybean agriculture and deforestation in Argentina highlights that short time periods analysis must be interpreted with caution because could be seriously affected by transient climatic, economic and technological conditions, including the role of livestock activities. Our analysis suggests that soybean-deforestation decoupling was a transient pattern associated to time-delays unrelated to government control, but rather to technological adjustment and particularities of the exchange ratios lasting for relatively short periods (e.g. 5 years). These conditions rapidly reversed into further re-coupling and re-accelerated deforestation under favorable macroeconomic context, in face of which national or local policies were not capable to stop coupled soybean expansion and deforestation.

In our study system, the dynamics of coupling/decoupling periods appears to be significantly influenced by the interaction between cattle ranching and soybean agriculture. Mechanized agriculture and cattle ranching apparently evolved from being alternative uses to become a complex of drivers with fluxes of capital and decisions among them that could be operating in other regions that need further research.

Q3 Uncited reference

ISAAA (2012).

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Appendix A. Supplementary data

Supporting information for remote sensing methods and results are included in Figs. A1 and A4 and Tables A1–A4. Additional figures for results are included in Figs. A2 and A3. Base data of production statistics and remote sensing results used for analysis are provided in Tables A5–A8.

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.09.007.

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