Global Environmental Change 45 (2017) 24–34

Contents lists available at ScienceDirect

Global Environmental Change

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

The role of soybean production as an underlying driver of deforestation in the South American Chaco

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ARTICLE INFO

Keywords:
Deforestation
Dry forests
Savannas
Soybean
Cattle ranching
Drivers of land-use change
Gran chaco

ABSTRACT

South America's tropical dry forests and savannas are under increasing pressure from agricultural expansion. Cattle ranching and soybean production both drive these forest losses, but their relative importance remains unclear. Also unclear is how soybean expansion elsewhere affects deforestation via pushing cattle ranching to deforestation frontiers. To assess these questions, we focused on the Chaco, a 110 million ha ecoregion extending into Argentina, Bolivia, and Paraguay, with about 8 million ha of deforestation in 2000–2012. We used panel regressions at the district level to quantify the role of soybean expansion in driving these forest losses using a wide range of environmental and socio-economic control variables. Our models suggest that soybean production was a direct driver of deforestation in the Argentine Chaco only (0.08 ha new soybean area per ha forest lost), whereas cattle ranching was significantly associated with deforestation in all three countries (0.02 additional cattle per hectare forest loss). However, our models also suggested Argentine soybean cultivation may indirectly be linked to deforestation in the Bolivian and Paraguayan Chaco. We furthermore found substantial time-delayed effects in the relationship of soybean expansion in Argentina and Paraguay (i.e., soybean expansion in one year resulted in deforestation several years later) and deforestation in the Chaco, further suggesting that possible displacement effects within and between Chaco countries may at least partly drive forest loss. Altogether, our study showed that deforestation in the Chaco appears to be mainly driven by the globally surging demand for soybean, although regionally other proximate drivers are sometimes important. Steering agricultural production in the Chaco and other tropical dry forests onto sustainable pathways will thus require policies that consider these scale effects and that account for the regional variation in deforestation drivers within and across countries.

1. Introduction

Agricultural expansion into tropical forests continues to be a main driver of global environmental change (Aide et al., 2013; Hansen et al., 2013), resulting in major carbon emissions (Baccini et al., 2012; Carlson et al., 2013), regional climate change (Butt et al., 2011; Silverio et al., 2015), widespread degradation of ecosystem services, and massive biodiversity loss (Metzger et al., 2006; Sala et al., 2000). Halting or slowing down tropical forest loss have thus become international priorities, and understanding what drives deforestation is essential to do so (Geist and Lambin, 2002). While the world's moist tropical forests have been in focus, the question of what drives deforestation in tropical dry forests and savannas remains understudied (Blackie et al., 2014; Lehmann, 2010; Parr et al., 2014) although deforestation there has been rampant recently, for example in Chaco in Argentina (Vallejos et al., 2015), the Cerrado in Brazil (Espirito-Santos et al., 2016), the Miombo woodlands (Mayes et al., 2015) or in Myanmar (Wohlfart et al., 2014).

This is particularly true for the tropical dry forests and savannas of South America. Rising agricultural commodity prices, an increasing integration of South American countries into world markets, favorable climatic conditions, the availability of cheap land and labor, as well as

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http://dx.doi.org/10.1016/j.gloenvcha.2017.05.001
Received 26 August 2016; Received in revised form 24 April 2017; Accepted 8 May 2017

increasing forest protection in the Amazon all have contributed to turning South America's tropical dry forests and savannas into major agricultural expansion frontiers, particularly regarding soybean and beef production (Garrett et al., 2013; Lambin et al., 2013; Parr et al., 2014). This has triggered widespread forest loss (Hansen et al., 2013), for example in the Cerrado in Brazil (Garcia and Ballester, 2016; Grecchi et al., 2014; LAPIG, 2014), the Chiquitania in Bolivia (Müller et al., 2012), or the Chaco in Argentina and Paraguay (Caldas et al., 2015; Kuemmerle et al., 2017). Given the speed of forest loss in these regions, understanding what drives these losses is important.

While the expansion of soybean cultivation and cattle ranching are both important proximate drivers of forest loss in South America's dry forests (Gasparri et al., 2013; Graesser et al., 2015; Volante et al., 2016), only a handful of studies quantitatively examined the relative importance of these drivers (Aide et al., 2013; Barona et al., 2010; Garcia and Ballester, 2016; Macedo et al., 2012; Rosa et al., 2015). Likewise, the underlying mechanisms that lead to soybean or cattle ranching expansion are not fully understood: there is an increasing recognition that soybean and cattle ranching form a linked system (Gasparri and le Polain de Waroux, 2014), with farmers engaging in both, with the goal to decrease their dependency on global prices and to reinvest revenues more efficiently (Goldfarb and Zoomers, 2013). For example, during a period of decreasing global soybean prices, it may be more profitable for farmers to invest in the acquisition of forests to expand cattle ranching, whereas under high soybean prices, pastures can be converted into croplands. Likewise, actors may clear land for pastures as a hedge against tightening deforestation regulations, with the ultimate goal of converting pastures to soybean production later (Baumann et al., 2016; le Polain de Waroux et al., 2016). Moreover, profits from pasture lands are generally less vulnerable to drought years compared to soybean cultivation (Gasparri et al., 2013). The empirical evidence for such linkages, however, remains weak.

Even where farmers do not engage in both soybean and cattle ranching, soybean expansion in one region may displace cattle ranching to another, such as in the Brazilian Amazon (Cohn et al., 2016; Gollnow and Lakes, 2014; Morton et al., 2006), from the Argentine Pampas to the Argentine Chaco (Gasparri et al., 2013), or from the Uruguayan Pampas and the Paraguayan Atlantic Forest region to the Paraguayan Chaco (Bertello, 2008; Gonzales, 2013; World Wildlife Fund, 2015). In all these cases cattle ranching appears to be the main proximate driver of deforestation, while soybean expansion may be ultimately underlying forest loss. This would mean that policies and conservation strategies have the potential to fall short if they only target cattle ranching and neglect the role of soybean as an underlying driver.

The Chaco, the largest remaining continuous stretch of tropical dry forest in South America (Portillo-Quintero and Sanchez-Azofeifa, 2010), is an interesting region to learn more about the direct and indirect role of soybeans as a driver of forest loss. Since the 1980s, technological innovation, rising global prices, favorable farming conditions, and the opening of regional land markets to internationally operating agribusinesses triggered rapid deforestation and agricultural expansion in the region, mainly for cattle ranching and soybean cultivation (Mastrangelo and Gavin, 2012; Zak et al., 2008, 2004). Because the Chaco extends into Argentina, Bolivia, and Paraguay, its cross-border setting provides a unique natural experiment to analyze drivers of deforestation under different policy settings, socio-economic conditions, and conservation paradigms.

While soybean cultivation and cattle ranching are both important proximate drivers of deforestation in the Chaco, their relative importance varies across the region. For example, in Argentina cattle ranching is the dominant proximate driver of deforestation (Volante et al., 2012), as many forest areas are being cleared for croplands, particularly soybeans (Baumann et al., 2017a). In contrast, in the Paraguayan Chaco almost all deforestation is to establish pastures, making it the dominant proximate driver there (Caldas et al., 2015; Carr, 2004), much like to northwestern Argentina (Volante et al., 2016). The relative importance of proximate drivers of deforestation also remains unclear because most studies to date rely on satellite imagery to map forest loss, typically for short time periods or small study regions. Existing work has often focused on assessing the spatial determinants of deforestation patterns (Gasparri et al., 2015; Killeen et al., 2008; Volante et al., 2016; Zak et al., 2008), rather than assessing the underlying drivers of these forest losses. An assessment of the role of soybean as a direct and indirect driver of deforestation for the Chaco as a whole is missing.

Consistent, high temporal- and spatial-resolution time series of deforestation in the Chaco (Hansen et al., 2013; Vallejos et al., 2015) provide new opportunities to analyze drivers of deforestation across national boundaries. Analyzing drivers of land-use change in a panel regression framework using time series data is a powerful way to detect possible causal relations (Butsic et al., 2015; Gibbs et al., 2016; Meyfroidt, 2015) for several reasons. First, panel regressions allow linking observed deforestation to changes in potential underlying drivers (e.g., market prices), while controlling for location factors that may govern the spatial patterns of change (e.g., soils, rainfall patterns, ownership, distance to markets). Second, time series models allow for detecting the impact of sudden changes in underlying drivers (e.g., policy interventions, new legislation, or currency devaluation), which may be hard to detect when focusing on longer time periods (Cameron and Trivedi, 2005). Finally, panel models are useful tools for discovering time lags in time series (Tao and Yu, 2012), and may thus reveal such time lagged responses of deforestation rates to underlying drivers. Yet, we know of no study that has assessed land-use change in the Chaco using such a statistical setup.

Our overarching goal was to quantify the drivers of forest loss for the Chaco as a whole, and to examine the role of soybean production as a direct and indirect driver of these losses. Specifically, we asked:

(1) What was the role of soybean and cattle ranching as proximate, direct drivers of deforestation in the Chaco between 2001 and 2012, and did the importance of these drivers vary among countries?
(2) How was soybean expansion outside the Chaco related to deforestation inside the Chaco, and were there time-lags in this relationship?

To answer these research questions, we tested the following hypotheses:

H1. Soybean cultivation is significantly related to deforestation at the district level.

H2. The national soybean area of a given country is significantly related to deforestation in the Chaco, regardless of proximate drivers of deforestation, suggesting displacement within countries.

H3. Soybean production in neighboring Chaco countries is significantly related to deforestation in the Chaco part of a given country, suggesting displacement across borders.

H4. There are time lags in the relationship between soybean cultivation outside, and deforestation inside the Chaco, suggesting links between cattle ranching and soybean actors.

2. Data and methods

2.1. Study area

Spanning 1.1 Million km^2, the Chaco is the second largest forest region in South America (Bucher and Huszar, 1999). The Chaco stretches from northern Argentina to southeastern Bolivia and northwestern Paraguay (Fig. 1a). Topography is mostly flat with elevation varying between 100 and 500 m. The climate is semi-arid with a dry season from April to September. Mean annual rainfall varies from

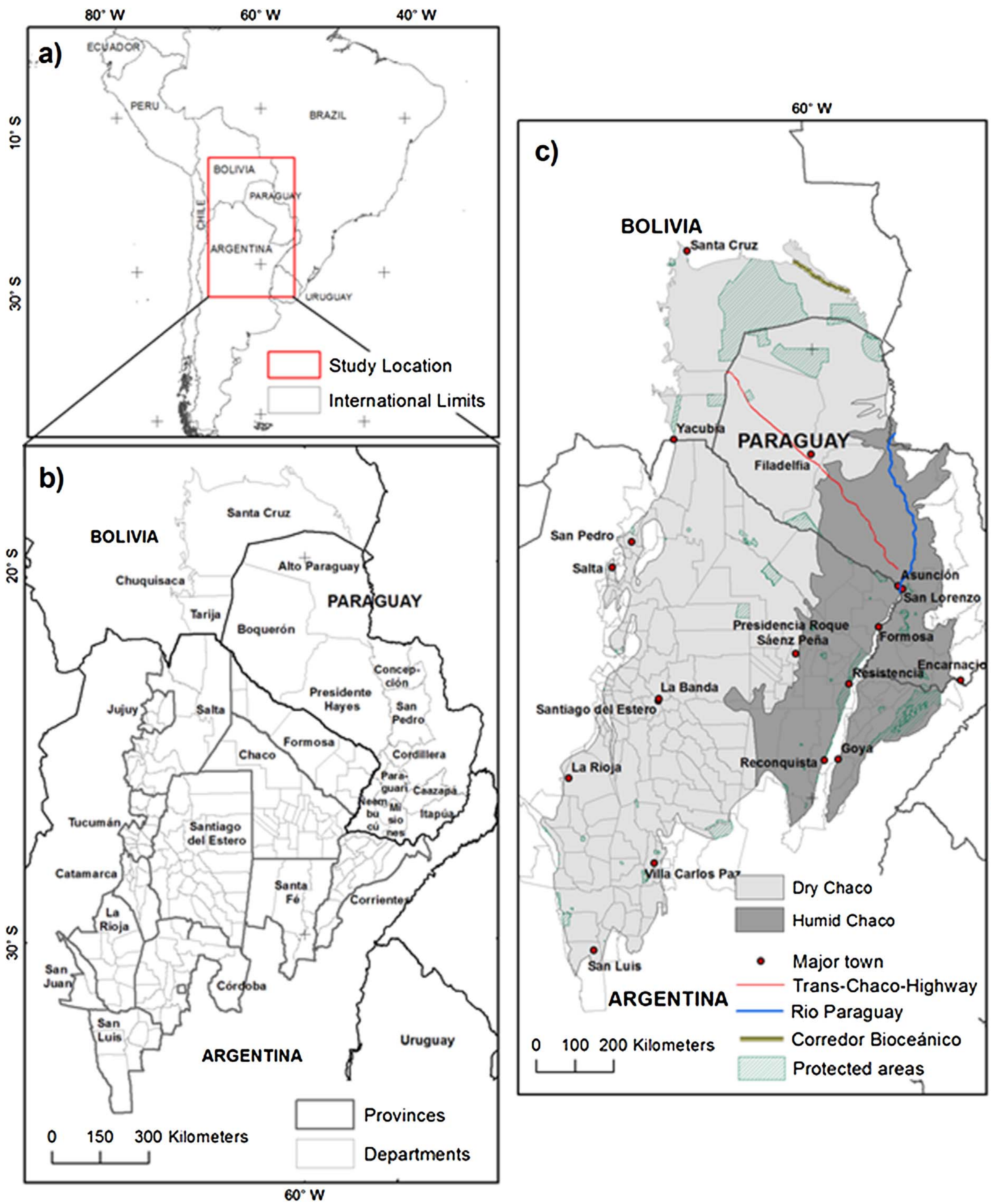

Fig. 1. Study area: a) Location of the Gran Chaco in South America; b) administrative subdivision of the Chaco into provinces (i.e., states) and departamentos (i.e., districts); c) major towns, ecosystem boundaries, protected areas and infrastructure.

450 mm to 1200 mm and decreases from east to west, resulting in a division into the wet Chaco (900–1200 mm) and dry Chaco (450–900 mm) (Bucher, 1982; Grau et al., 2005). Soybean, the region's major crop, is currently limited to areas above ~500 mm rainfall (Murgida et al., 2014). Soils are neutral or slightly alkaline across the entire Chaco and are generally characterized by high fertility, although some soils (e.g., saline soils, regularly flooded soils) are generally less suited for crop cultivation (Bucher and Huszar, 1999). The natural vegetation comprises a mosaic of xerophytic forests, shrublands, palm savannas, natural grasslands, and wetlands (Bucher, 1982; Bucher and Huszar, 1999; Prado, 1993).

The Chaco has a long land-use history, which until World War II mainly included small-scale subsistence agriculture and extensive cattle ranching. In Argentina, during the last 30 years, forests were mainly cleared for agricultural use (Campos-Krauer and Wisely, 2011; Gasparri and Grau, 2009). Agriculture is increasingly carried out by medium- to large-scale companies cultivating annual crops such as wheat, sunflower, sorghum, corn and soybean, or cattle production on implanted pastures (Zak et al., 2008). Agricultural activities are highly subsidized in Argentina, particularly since the economic crisis in 2001

(Leguizamon, 2014), and the vast majority of commodities are for export purposes. In the Paraguayan Chaco land-use change started in the beginning of the 1960s when cattle ranching began to expand (Campos-Krauer and Wisely, 2011), but has especially expanded recently, with rapid deforestation following the introduction of more efficient cattle ranching practices including the introduction of highly productive, exotic grasses (Cabrera et al., 2001; Hecht, 1975; Quinlan et al., 1980). This development was further promoted by the construction of the Trans-Chaco-Highway between Paraguay and Bolivia (Fig. 1c) (Fatecha, 1989; Killeen et al., 2007, 2008), and today Paraguay is a major beef exporter, strongly supported by governmental policies through almost unrestricted ability for agricultural expansion (Vazquez, 2013). Land-use changes in the Bolivian Chaco are thought to be in part the result of unusual high rainfalls in the last decades, which facilitated the expansion of soybean cultivation around Santa Cruz and along the Corredor Biocéanico (Fig. 1c) (Redo et al., 2011), whereas agriculture is not widespread along the Andean foothills in the west (Bucher and Huszar, 1999; Müller et al., 2012).

Only a small share of the Chaco is protected, overall accounting for only about 10%. In addition, protected areas are unevenly distributed across the Chaco, with Bolivia having the largest area under protection (36% of the Bolivian Chaco are protected), whereas in Argentina (~7.5%) and Paraguay (~6.5%) this share is much lower.

2.2. Input data

The dependent variable in all our models was the area of forest loss, which we derived from satellite-based maps. Specifically, we used the global product of forest loss between 2000 and 2012 (Hansen et al., 2013), from which we extracted the total deforestation area per year for each district (i.e., *departamento*, Table 1).

As explanatory variables, we used variables capturing production indices of global market and costs and spatial control variables. As production indicators we acquired statistical data on (a) soybean area [ha], (b) soybean production [t], (c) soybean yield [t/ha], and (d) cattle heads [#]. For cattle heads, we assumed a constant stocking rate across our entire observation period (i.e., 2001–2012, FAOSTAT (2015)). We acquired indices a–c from national statistics at the district level for each year between 2001 and 2012 (IICA, 2014; INE, 2013; Observatorio Bovino, 2014; SIIA, 2014). In terms of cattle numbers, we used district level data for each year between 2001 and 2012 from national inventories for Bolivia and Paraguay. For Argentina, district-level data (i.e., *departamentos*) were only available for the years 2002 and 2010, whereas state-level data (i.e., *provincias*) were the most fine-scale data available for the other years. We disaggregated these province-level data to the district-level using district-level data from the last year in which data was available as weights. We used the last year for which data were available at the district level (available years 2002 and 2010) and assumed proportions among districts had not changed.

Global market and costs indices we acquired from the World Development Indicators Dataset (World Bank, 2015). Specifically, we used country-level development indicators, such as commodity price data for soy and beef, or currency exchange rates. Commodity prices drive agricultural expansion, and thus deforestation, because during times of high prices, land owners receive higher revenues which in case of the Chaco are primarily being invested into new land acquisitions (Gasparri et al., 2013). Changes in currency exchange rates may further accelerate this process as they strongly influence profits, particularly during times of currency devaluation (Gasparri et al., 2013). Additionally, we used fuel prices (i.e., diesel prices) as an indicator of internal costs, which are available bi-annually from the Food and Agricultural Organization (FAO) statistical database (FAOSTAT, 2015).

Spatial control variables included the travel time to cities with over 50,000 inhabitants for the year 2000, using the Global Rural Urban Mapping Project (GRUMP, SEDAC (2011)), the mean travel time to major grain harbors (Gardel, 1999), and the proportion of each district inside protected areas based on the World Database on Protected Areas (WDPA, 2007). Lastly, we calculated a suite of environmental variables at the district level, including mean annual temperature [C], mean annual precipitation [mm], mean warmest month [C], and mean coldest month [C], from the ClimateSA dataset (Hamann et al., 2013; Wang et al., 2012). This should control for some areas in the Chaco being too wet or too dry for soybean production (Baumann et al., 2017b), which should favor pasture expansion compared to soybean expansion in these areas.

We checked for potential multicollinearity in our predictors by calculating a correlation matrix. In case of a correlation coefficients > 0.8 between two variables (Menard, 2002), we kept the variable with the higher explanatory power. This resulted in a set of 19 variables (Table 1), which we divided into three variable sets, depending on the hypothesis we tested.

2.3. Correlation analyses

To assess whether soybean expansion is the main cause of deforestation (H1) or cattle production, we related soybean area and cattle heads to deforested area at the district level. In both cases, we generated a scatter-plot per district containing 12 observations (i.e., one per year), calculated Spearman's correlation coefficient, and visualized correlation coefficients that were significantly different from zero in a map.

2.4. Panel regression model

We explored the role of soybean and cattle ranching as drivers of deforestations by estimating a linear panel model in the general form:

$$y_{i,t} = \theta S_{i,t} + \gamma C_{i,t} + BX_{i,t} + u_{i,t} \qquad (1)$$

where y is the deforested area in district i and year t, S is a vector of soybean production variables (i.e., soybean area, soybean yield) in district i and year t, C is the number of cattle heads in district i and year t; X is a vector of control variables that influence y in district i and year t, and u is the random error component. We estimated all models using fixed and random effects and selected the better-performing model based on Hausmann's specification test (Baltagi, 2008).

We assessed the role of soybean and cattle ranching as proximate drivers of deforestation across the three countries in the Chaco, Argentina, Paraguay and Bolivia (H1, variable set 1) in two ways. First, we interacted the soybean area and cattle heads variables in our global model with a country dummy to uncover the partial effect of the two drivers in each country. Second, we split our dataset by country (i.e., Argentina = 158 districts, Paraguay = 10 districts and Bolivia = 3 districts), and estimated separate linear panel models for Argentina and a combined dataset for Bolivia and Paraguay.

To quantify whether soybean expansion outside the Chaco is significantly related to deforestation inside the Chaco (H2, H3), we expanded the country-level panel models by including variables on the national soybean area of Argentina, Paraguay, and Bolivia between 2001 and 2012 (Table 1, variable set 2). Specifically, we tested (i) whether deforestation in the Argentinean Chaco was related to the national soybean area of Argentina, indicating possible displacement between countries, and (ii) whether deforestation in the Paraguayan and Bolivian Chaco was related to the national soybean area of Paraguay and Bolivia, indicating possible displacement inside these countries (Fig. 4). We also tested for possible displacement effects across borders by (iii) including the national soybean area of Argentina in the Paraguay/Bolivia model.

We assessed possible time lags in the influence of soybean cultivation on deforestation in the Chaco (H4) in two ways. First, we identified lags of soybean area that are associated with deforested area by calculating cross-correlation functions of the form:

Table 1
Variables used in the statistical analyses.

Variable	Expected impact on response variable (Deforestation Area [ha])	Years available	Variable Set	Source
Deforestation Area [ha]		2001–2012		Hansen et al. (2013)
Soybean area [ha]	Increasing soybean area leads to an increase in deforestation area	2001–2012	1	IICA (2014); INE (2013); Observatorio Bovino (2014); SIIA (2014)
Soybean production [t]	Increasing soybean production leads to an increase in deforestation area	2001–2012	1	IICA (2014); INE (2013); Observatorio Bovino (2014); SIIA (2014)
Cattle heads [#]	Increasing cattle production leads to an increase in deforestation area	2001–2012	1	IICA (2014); INE (2013); Observatorio Bovino (2014); SIIA (2014)
Soybean world market prices [US-$]	High commodity prices increase the incentive to expand agriculture	2001–2012	1	World Bank (2015)
Cattle meat world market prices [US-$]	High commodity prices increase the incentive to expand agriculture	2001–2012	1	World Bank (2015)
Exchange-rate peso to US-$	High conversion rates increase production costs, thus decreasing profits and agricultural expansion	2001–2012	1	World Bank (2015)
Diesel prices	Low diesel prices increase agricultural profits and incentives agricultural expansion	2001–2012	1	FAOSTAT (2015)
Travel time to major cities [min.]	Shorter travel time decreases transportation costs and increase profits; thus incentivizing agricultural expansion		1	SEDAC (2011)
Mean travel time to grain harbors [min.]	See above		1	Gardel (1999)
% Protected areas	Protected areas restrict/limit the area available for agricultural expansion		1	WDPA (2007)
Mean annual temperature [C]	Higher temperatures increase soybean productivity, thus incentivizing agricultural expansion	2001–2009	1	Hamann et al. (2013)
Mean annual precipitation [mm]	Higher precipitation generally increases soybean productivity, thus incentivizing agricultural expansion	2001–2009	1	Hamann et al. (2013)
Mean temperature of warmest month [C]	Extreme climatic conditions potentially limit soybean productivity	2001–2009	1	Hamann et al. (2013)
Mean temperature of coldest months [C]	See above	2001–2009	1	Hamann et al. (2013)
National soybean area ARG [ha]	Larger national soybean area increase deforestation in the Chaco	2001–2012	2	FAOSTAT (2015)
National soybean area PAR/BOL [ha]	See above	2001–2012	2	FAOSTAT (2015)
National soybean area ARG with time lags [ha]	See above	2001–2012	3	FAOSTAT (2015)
National soybean area PAR/BOL with time lags [ha]	See above	2001–2012	3	FAOSTAT (2015)

$$x_{t+h} \sim y_t \, for \, h \in \{-6, \ldots, +6\} \quad (2)$$

where x describes the soybean cultivated area in year t plus the time-lag h [years], and y the deforested area in year t. Using these cross-correlations, we explored possible lags between (i) national soybean area in Argentina and deforestation in the Argentinean Chaco, Paraguayan and Bolivian Chaco and (ii) national soybean area in Paraguay and Bolivia and deforestation in the Paraguayan and Bolivian Chaco. Second, we used the country-level panel models from above and included time-lag variables capturing the national soybean area in Argentina, Paraguay and Bolivia in the years 2000–2011, 1998–2008, 1996–2007 and 1991–2002 (Table 1, variable set 3).

We tested all panel models for heteroscedasticity and serial cross-correlation using the Breusch-Pagan (Breusch and Pagan, 1979) and the Breusch-Godfrey/Wooldridge tests (Godfrey, 1996). In cases where the residuals showed heteroscedasticity, we used the robust covariance matrix estimator (Arellano estimator), which produces robust standard errors while controlling for serial correlation (Stock and Watson, 2011). To assess the goodness of fit of our models, we used the adjusted R^2.

3. Results

Deforestation in the Chaco was widespread between 2001 and 2012, with a total of 7.8 million ha (Mha) deforested. Yet, deforestation rates varied substantially, with higher rates during 2003–2005 (on average ~600,000 ha of forest loss per year), 2007–2008 (~920,000 ha/year) and 2010–2011 (~890,000 ha/year), and somewhat lower deforestation rates between 2001 and 2002 (~290,000 ha/year) and 2005–2006 (~540,000 ha/year).

Soybean area increased between 2001 and 2012 from 2.3 to 5.2 Mha in the Chaco (+126%). The largest soybean expansion occurred in Argentina, from 1.6 Mha in 2001 to almost 4 Mha in 2012 (+150%, Fig. 2). Soybean expansion was lower, but still substantial, in the other two countries (0.5 Mha to 1 Mha in Paraguay, and 0.2 to 0.35 Mha in Bolivia respectively (Fig. 2)). Likewise, cattle heads in the Chaco increased between 2001 and 2012 from 21 to 27 million heads, equaling 28.5%. In the Argentine Chaco cattle increased between 2001 and 2006 from 12 to 15 million heads (+25%, Fig. 2). However, this increase was not uniform over the entire study period, with even a slight decrease of −6.7% between 2006 and 2011. In the Paraguayan and Bolivian Chaco the number of cattle increased steadily from 7 to 10.5 million heads (+50%) in Paraguay and from 1.2 to 1.7 million heads (+42%) in Bolivia (Fig. 2).

The correlation between deforestation area and soybean area at the district-level varied substantially across our study region, but was generally low (Fig. 3). Only five districts showed correlation coefficients higher than 0.5, all of which were located in the Argentine Chaco, with the highest positive correlations in Almirante Brown and San Justo ($r > 0.8$). Ten districts showed weak correlations ($r < 0.2$) and 21 district had a negative correlation between deforestation and soybean area (Fig. 3, e.g., districts in the Argentinean provinces Santa Fé, Chaco, Tucuman, or the Paraguayan districts of Concepcion, San Pedro, Itapúa and Caazapá).

Correlating deforested area and cattle heads between 2001 and 2012 showed almost the opposite pattern, with generally high correlation across much of our study area (Fig. 3). We found the highest correlation coefficients in Copo in Argentina ($r > 0.8$), Alto Paraguay in Paraguay, and Santa Cruz in Bolivia ($r > 0.7$), whereas 23 districts showed weak correlations ($r < 0.2$). Negative correlations between deforestation and cattle heads were rare and evident only in the east of the Paraguayan Chaco and in some districts in Argentina (Fig. 3).

The global panel regression model performed better under random effects compared to under fixed effects (adj. R^2 of 0.15 compared to adj. R^2 of 0.09). When introducing interaction terms, model performance of the fixed effects model increased substantially (R^2 of 0.22). All three model parameterizations (i.e., random effects, fixed effects and fixed effects with interaction terms) showed that soybean area and soybean yield were both positively related to deforestation (0.03–0.08 ha deforestation per additional hectare of soybean area increase, and 0.39–0.53 ha deforestation per t/ha soybean yield increase; for p-values indicating significance of the coefficients please refer to Table 2). Likewise, the number of cattle heads (0.01–0.02 ha deforestation per additional cattle), and world market price for cattle meat (about 2300–2600 ha additional deforestation per US$ increase) were related to deforestation, and so was the exchange rate (0.45–2.22 ha deforestation per unit increase in the local currency). Contrary to that, mean annual precipitation and mean annual temperature were not related to deforestation (with exception for temperature in the fixed effects model, Table 2). Including the soybean area in Paraguay and Bolivia as predictors in the global model showed negative effects on deforestation in the Chaco (−0.09 and −0.29, respectively), whereas the number of cattle heads had a positive effect (0.02 for Paraguay and Bolivia; Table 2).

Our country-level models showed different results for Argentina on one hand, and for Bolivia and Paraguay on the other. For Bolivia and Paraguay, national soybean area was negatively related to deforestation (−0.04) and the number of cattle heads was positively related to deforestation (0.03; Table 3). Likewise, exchange rates (2.02–3.19) and world soybean prices (+25.2) were positively related to deforestation, whereas climate variables were less important (Table 3). Including the soybean area of Argentina as a whole in the model for the Bolivian and Paraguayan Chaco showed a negative relationship between soybean area and deforestation (−0.00009, model specification 2). When testing for possible time-delayed effects, we found the soybean area of Paraguay and Bolivia had the strongest relation to deforestation with a 3-year lag (0.0005, model specification 3, Table 3).

For Argentina, a different picture emerged. Soybean area in the Chaco was positively related to deforestation (+0.08 in all three model specifications, Table 4), and so were cattle heads but this relationship was weaker (+0.01 in all three model specifications). Mean annual temperature was negatively related to deforestation, and only significant for model specifications 2 and 3, whereas precipitation was not significant in any model (Table 4). Deforestation in the Argentine Chaco was positively related to the soybean area in Argentina as a whole, both without a time-lag (+0.002) as well as with a time-lag of 1-year (+0.0001, Table 4)

The cross-correlation analysis comparing soybean area and deforestation in the Chaco showed that these two variables were generally most strongly related to each other without a time-lag. Only in case of national soybean area in Argentina and deforestation in Paraguay (time-lag −1, $r = 0.65$), and national soybean area in Paraguay and deforestation in the Paraguayan Chaco (time-lag − 1, $r = 0.6$), we found a time-lag (Fig. 4).

4. Discussion

The tropical dry forests of Latin America are a global hotspot of deforestation, but our understanding of what drives deforestation, particularly regarding displacement effects within and among countries, remains unclear. We assessed the relative importance of the expansion of cattle ranching and soybean cultivation as direct and indirect drivers of deforestation in the South American Chaco between 2001 and 2012 using a panel regression approach. We found that cattle ranching was the most important direct (i.e., proximate) driver of deforestation in the Chaco. Only in the Argentine Chaco larger areas of forests were directly replaced by soybean. However, we found strong relationships between deforestation occurring inside the Chaco and soybean expansion outside the Chaco, possibly because pasture lands outside the Chaco, such as in the Pampas or Atlantic Forest regions, were converted into soybean fields, displacing pasture lands into new areas, including in the Chaco. Thus, our study adds evidence that deforestation in the Chaco may at least in part be due to tightening

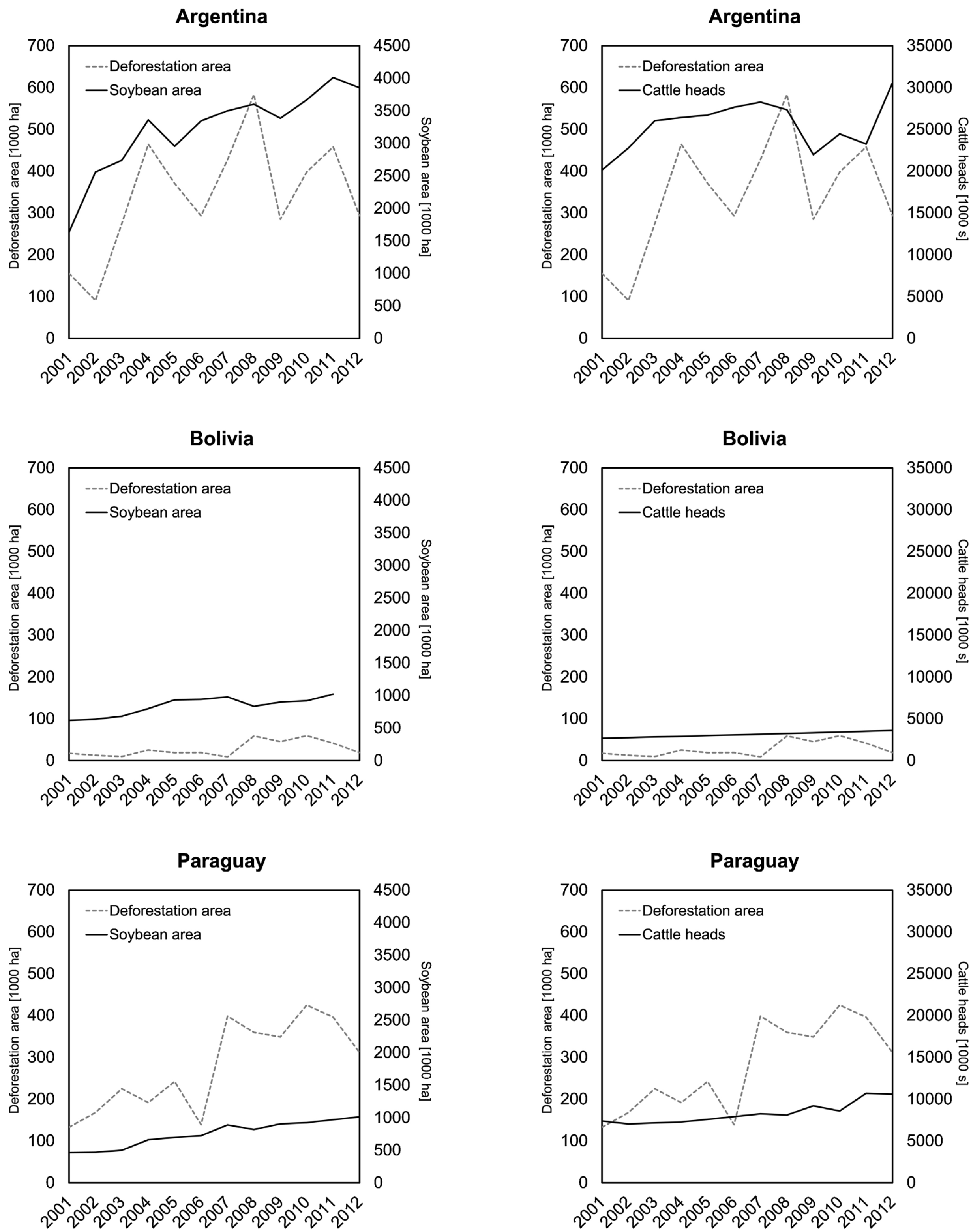

Fig. 2. Deforestation area in relation to soybean area and cattle heads for the three countries of the Chaco, Argentina (top row), Bolivia (middle row), and Paraguay (bottom row). The x-axes in all cases represent the years in our analysis, and the left y-axes denote the amount of deforestation area [thds. ha]. The right y-axes represent in the three graphs on the left side the soybean area [thds. ha], in the three graphs on the right side the amount of cattle [thds heads].

control and stronger deforestation policies in other regions inside the Chaco countries, as well as from other countries, where soybean production expands (i.e., displacement effects). This suggests that soybean expansion in South America, regardless of where it occurs, is an underlying driver of deforestation in the Chaco. From a policy perspective, this highlights the need for cooperation across scales, from local to eco-regional scale, and across national boundaries to prevent unwanted or surprising outcomes.

A number of studies have previously assessed drivers of deforestation quantitatively in the Chaco (Campos-Krauer and Wisely, 2011; Gasparri et al., 2013; Grau et al., 2005; Zak et al., 2008), though often for small sub-regions of the Argentine Chaco, relying on snapshots of

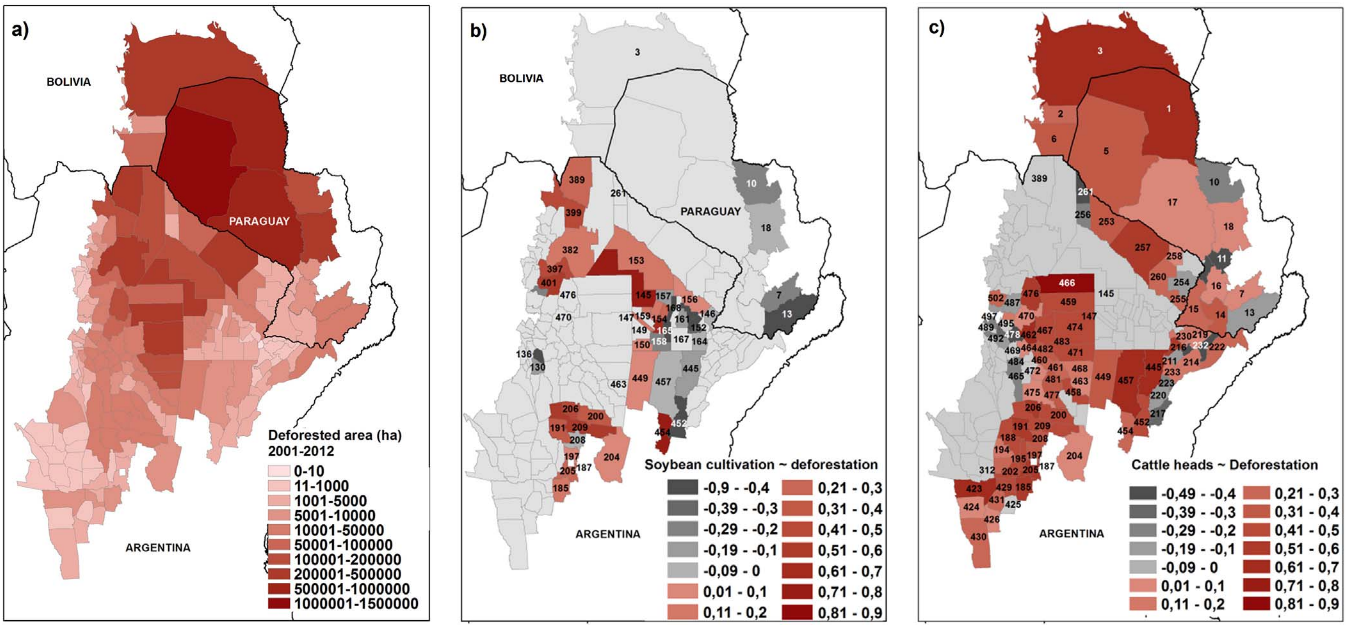

Fig. 3. (a) Deforested areas [ha] summarized at the district level; (b) Spearman correlation coefficients of soybean area and deforestation and (c) Spearman correlation coefficients of cattle heads and deforestation.

Table 2
Panel data regression coefficients of the global panel model (i.e., the model for the Chaco as a whole) under the different model parameterizations (Model I: Random effects model, model II: fixed effects model, model III: fixed effects model with interaction terms).

	Random effects	Fixed effects	Fixed effects with interaction terms
Soybean area [ha]	0.03 ***	0.04 .	0.08 **
Soybean yield [t/ha]	0.39	0.53 *	0.39 .
Cattle heads [#]	0.01 ***	0.02 **	0.01 *
World price cattle [US $/kg]	2335.6 ***	2583.7 **	2304.3 **
Exchange rate [LCU/US$]	0.45	2.22 **	2.09 ***
Mean annual temperature [°C]	150.5	−272.9 **	−282.5
Mean annual precipitation [mm]	−0.2	1.37	1.18
Mean travel time to grain harbors [min]	7.39 ***		
Mean travel time to major cities [min]	9.45 **		
% Protected areas	−0.001		
National soybean area PAR [ha]			−0.09 **
National soybean area BOL [ha]			−0.29 ***
Cattle heads PAR [#]			0.02 *
Cattle heads BOL [#]			0.2 ***
Adj. R-squared	0.15	0.09	0.22

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

land use/cover, or without considering post-deforestation land use. We expand on this knowledge base by covering the entire Chaco in Argentina, Bolivia, and Paraguay, and by analyzing detailed time series of deforestation and its potential drivers. This allowed us to go beyond assessing the spatial determinants of deforestation patterns to more closely assess the underlying drivers of these forest losses, particularly in terms of the role of soybean expansion.

Our first hypothesis was that deforestation is directly related to the expansion of soybean cultivation in the areas where deforestation takes place. Our results, both from the correlation analyses and the panel regressions, suggest that soybean expansion was only a direct driver of deforestation in parts of the Argentine Chaco, whereas in other regions

Table 3
Panel data regression coefficients of the country-level model for Bolivia and Paraguay under the three model parameterizations (Model I: without considering soybean areas outside the Bolivian and Paraguayan Chaco, model II: considering the national soybean area of Argentina, model III: considering the national soybean area of Bolivia and Paraguay with a time-lag).

	Model I	Model II	Model III
Soybean area [ha]	−0.04 **	−0.04 **	−0.04 *
Soybean yield [t/ha]	1.59	2.07	1.98
Cattle heads [#]	0.03 ***	0.03 ***	0.03 ***
World price soybean [US$/kg]	25.2 *		
Exchange rate [LCU/US$]	3.19 ***	2.02 ***	2.69***
Mean annual temperature [°C]	156.8	−1007.3	−1429.8
Mean annual precipitation [mm]	−0.94	−0.39	−0.89
Mean temperature warmest month	−2835.5 ***	−3412.8 ***	−3130.1 **
National soybean area ARG [ha]		−0.00009 *	
National soybean area BOL/PAR [ha] − Time-lag-3			0.0005 .
Adj. R-squared	0.29	0.27	0.27

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

Table 4
Panel data regression coefficients of the country-level model for Argentina under the three model parameterizations (Model I: without considering soybean areas outside the Argentine Chaco, model II: considering the national soybean area of Argentina, model III: considering the soybean area of Argentina with a time lag).

	Model I	Model II	Model III
Soybean area [ha]	0.08 **	0.08 **	0.08 **
Soybean yield [t/ha]	0.29	0.26	0.26
Cattle heads [#]	0.01 **	0.01 **	0.01 **
World price cattle [US$/kg]	2104.4 **		
Mean annual temperature [°C]	−188.5	−454.8 **	−476.1 **
Mean annual precipitation [mm]	1.25	0.39	0.14
National soybean area ARG [ha]		0.002 **	
National soybean area ARG [ha] − Time-lag −1			0.0001 *
Adj. R-squared	0.08	0.07	0.07

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

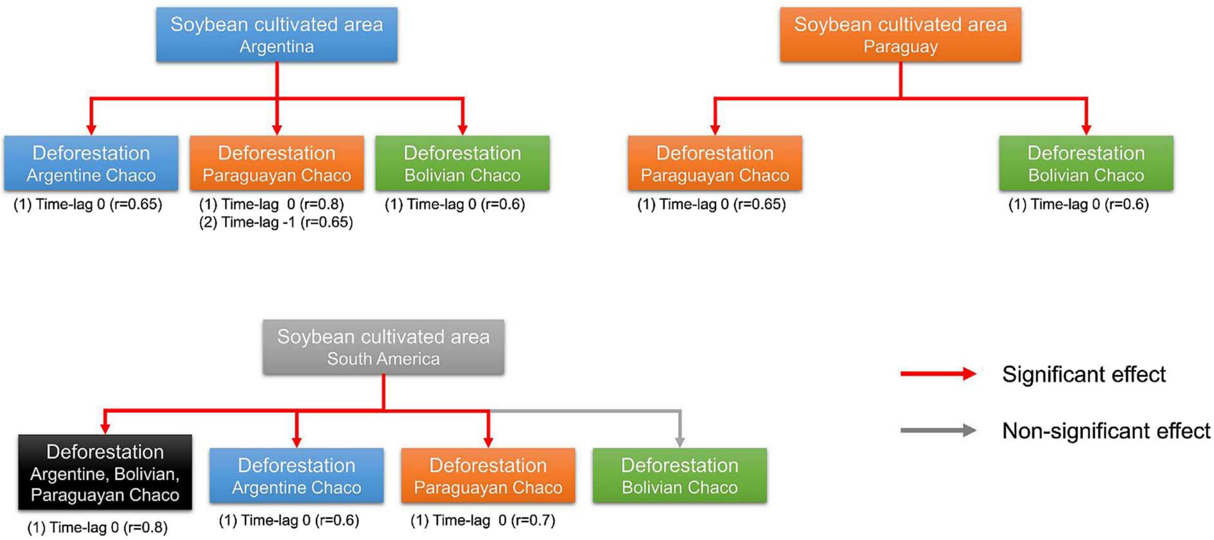

Fig. 4. Summary of the sample cross-correlation plots on the basis of the product moment correlation coefficient.

in Argentina and in the Paraguayan and Bolivian Chaco, cattle ranching was the dominant direct driver of deforestation area but not the soybean cultivated area. Our results thus confirm the mostly descriptive and qualitative findings from prior work for smaller regions in the Argentine Chaco (Volante et al., 2016), and the Paraguayan Chaco (Baumann et al., 2017b; Caldas et al., 2015). World market prices for cattle meat and soybean have increased over our study period, making it attractive for farmers to expand production (Leguizamon, 2014; Richards et al., 2012; World Bank, 2015). The strong association of deforestation with ranching expansion can be explained by many areas in the Chaco being only marginally suited for soybean cultivation, but well-suited for industrialized ranching. Moreover, expanding cattle ranching is associated to comparatively lower cost to deforest and prepare the land than when expanding crop production (Graesser et al., 2015; Manuel-Navarrete et al., 2009). Thus, establishing cattle ranching is seen by many producers as an intermediate, less capital-intensive step towards industrialized agriculture. Finally, zoning prevents the expansion of cropping but allows the expansion of some forms of ranching in some areas of the Argentina Chaco (Piquer-Rodríguez et al., 2015).

Interestingly though, soybean expansion at the national level was strongly related to deforestation rates in the Chaco in all three countries. We suggest this is at least partly a result of agricultural intensification elsewhere and a displacement of pastures into the Chaco. For example, soybean expansion in the Pampas region in Argentina, and the Paraguayan Atlantic Forest have been widespread (World Wildlife Fund, 2015), mainly over former pastures. The resulting profit is often re-invested in land acquisitions for pasture expansion in the Chaco, either by actors that have been selling land or by the same actors engaging in soybean production and cattle ranching (Barona et al., 2010; Gasparri and le Polain de Waroux, 2014; Morton et al., 2006). This is additionally supported by our correlation analyses, which indicates that districts with strong correlations between cattle heads and deforestation are located close to districts where soybean expansion was high, but uncorrelated with deforestation, indicating that in these districts soybean expanded mainly over existing pasture areas and displaced pasture to adjacent districts, similar to what has been seen in Mato Grosso, Brazil (Arima et al., 2011; de Sa et al., 2013; Gollnow and Lakes, 2014; Richards et al., 2014). Overall, our analysis supports the hypothesis that the national focus on soybean expansion is driving deforestation in the Chaco, though it is partially hidden through the dominance of pasture expansion there.

Lastly, it appears that while soybean expansion outside and deforestation inside the Chaco are related, they are not necessarily ongoing simultaneously. Instead, our models highlight, at least in some cases, time lags (hypothesis 4). Further, all identified time-lags had a negative sign, indicating that deforestation occurred prior to an increase in soybean expansion. While not entirely enabling us to draw inference, this may be an indication of two things: first, agricultural actors in South America are increasingly engaged in both, cattle ranching and soybean cultivation. The coordination of these two activities is fast, possibly by establishing new pastures and moving cattle to the new site in one year, and by converting previous pastures into soybean areas during the subsequent year. Second, this process may be occurring at the national level (e.g., between the Atlantic Forests and the Chaco in Paraguay, and the Pampas region and the Chaco in Argentina), but also across borders (e.g., between Argentina and the Paraguayan Chaco), further highlighting the agility of agricultural actors not only in the Chaco, but across South America. Overall, our results support the hypothesis of existing time-lags between deforestation and soybean expansion.

Summarizing our hypotheses tests shows that the deforestation frontier in the Chaco is likely primarily fueled by the global demand for soybean. The detection of this relationship is challenging because the underlying mechanisms are complex, and partially out of phase with one another. Considering the possibly strong underlying role of soybean expansion is particularly important when developing and implementing strategies to reduce deforestation. Such strategies will have to consider the changing nature of actors that operate from within and outside the Chaco (Gasparri, 2016), as well as local communities (Ceddia et al., 2015) that use the resources provided by the Chaco. Further, as the Chaco becomes increasingly vulnerable to deforestation due to land-use changes elsewhere, our study highlights the need to assess land-use changes in a comprehensive way across larger regions, considering even regions that fall outside an area targeted by policies, and combining remote-sensing data on land-use change with statistical information.

Some uncertainties resulting from our analysis need mentioning. First, as a result of strong multi-collinearities among our predictors and a different number of observations in our models, a direct comparison of the regression coefficients between the models was not possible. We overcame this problem by using interaction variables for soybean and cattle heads in the global panel model. Second, we caution that our dependent variable (i.e., deforestation area) does not contain any information about post-deforestation land use/cover, and thus may include natural disturbances such as fires. However, we consider this effect small in comparison to the forest losses for agricultural use. Third, we did not consider soybean area or production in Brazil as covariates. While there have been Brazilian farmers purchasing land

and establishing operations in Paraguay, these mainly engage in cattle ranching, and to our knowledge there is currently too little evidence to link this expansion to Brazilian soybean production (e.g., via displacement or rebound effects). Moreover, the huge soybean production in Brazil and the fairly small number land deals suggest that the effect would be hard to capture with our models. Fourth, while our models consider several important variables driving deforestation in the Chaco, additional variables that may influence agricultural expansion would have been great, such as land prices or land tenure. However, to our knowledge no Chaco-wide dataset on such variables exist. Lastly, in our study we focus exclusively on one type of croplands (i.e., soybean), although other crops (e.g., corn, cotton, sorghum) are cultivated in the Chaco as well, though to a lesser extent.

Overall, our study shows that the Chaco is currently losing forests at an alarming pace, and that deforestation is primarily fueled by the global demand for soybean. It is likely that this demand will stay high and even increase further in the future due to increasing global population changing diets. The Chaco seems, from an agricultural perspective, a prime region to help fulfilling this demand. On one hand, the region is suitable for agricultural production, especially for drought-resistant soybean variants, and agricultural expansion is strongly promoted as a policy of economic development. On the other hand, land prices are still comparatively low there, and nature protection is underdeveloped in the Chaco, allowing for almost unrestricted agricultural expansion (Kuemmerle et al., 2017). Land-use strategies regulating agricultural expansion in the Chaco while helping to protect natural areas are urgently needed to conserve the Chaco and its unique biodiversity. Such policies will have to be developed at the large scale, possibly across countries, but adapted locally to consider the regional differences behind changing land-use dynamics.

Acknowledgements

We gratefully acknowledge support for this research by the German Research Foundation (DFG, KU 2458/5-1), by the Federal Ministry of Science and Education (BMBF, PASANOA 031B0034A), by the Einstein Foundation Berlin and the Argentine National Agricultural Technology Institute (INTA, PNNAT 1128052). We are grateful for comments made by the two anonymous reviewers, whose comments greatly improved the manuscript.

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