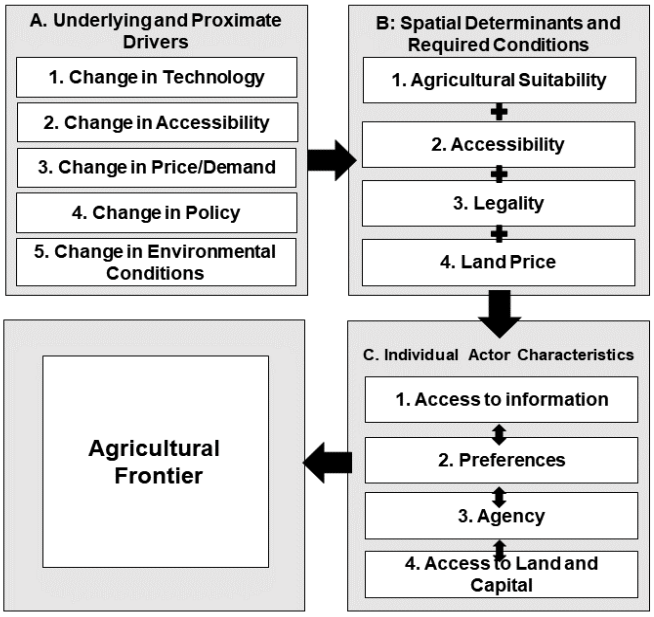
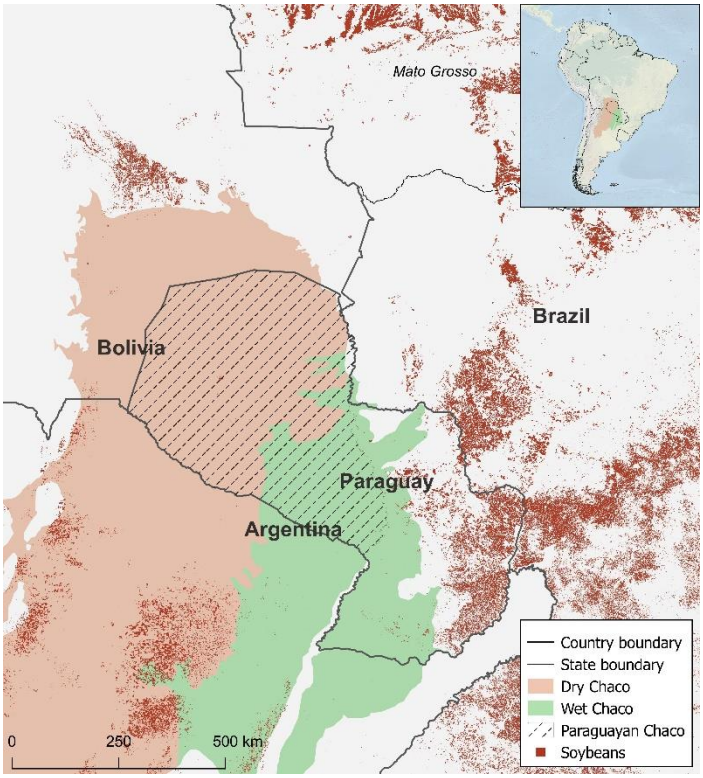
Supplementary Online Material - The Paraguayan Chaco at a Crossroads: Drivers of an Emerging Soybean Frontier

1 Proposed conceptual framework of agricultural frontier expansion dynamics



Adapted from Frey et al. (2018), Le Polain de Waroux et al. (2018), Jepson (2006), and Angelson (2010)

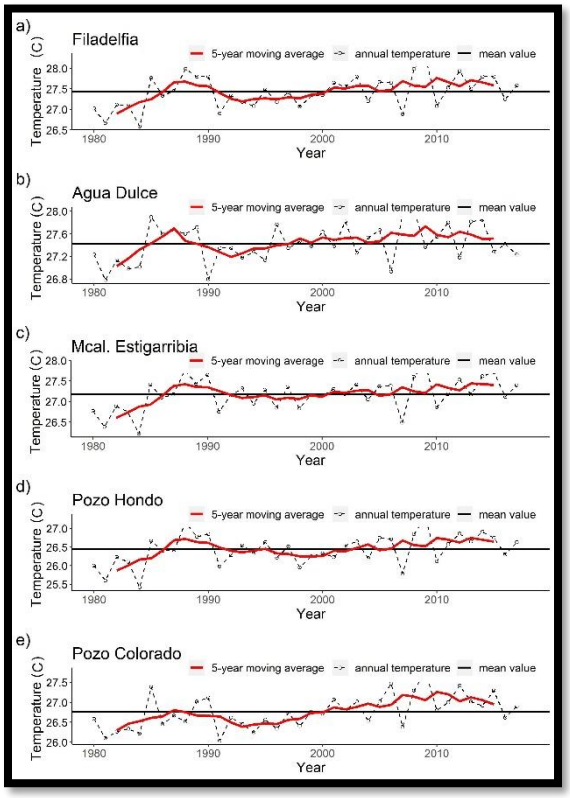
2 South American Soybean Production regions



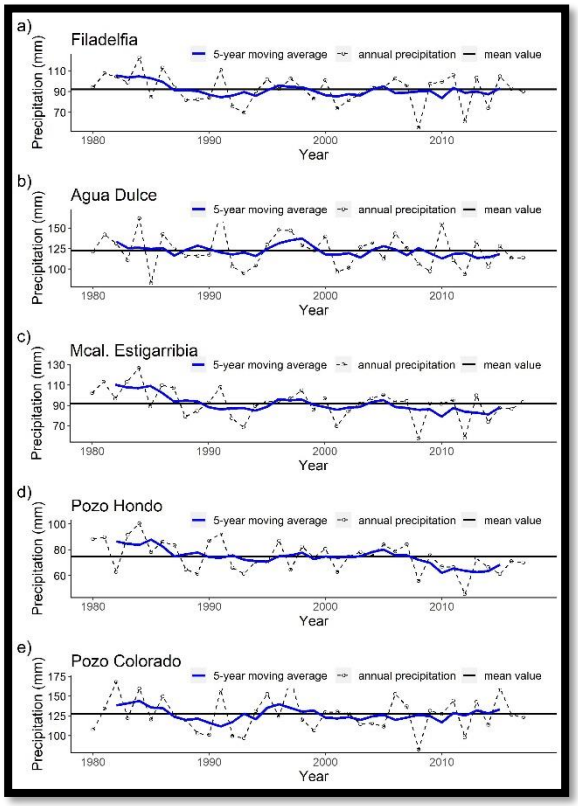
The Paraguayan Chaco in relation to 2018 soybean coverage in South America (University of Maryland/Hansen, M. C. (Unpublished) provided SEI/Trase)

3 a-b Yearly average temperature (3a) and precipitation for the Paraguayan Chaco (3b)

3a



3b



Yearly average temperature and precipitation between 1980-2017 based on several representative locations in the Paraguayan Chaco between April and November based on Harris et al. (2020) CRU dataset. (Harris et al. 2020)

4 Actors Engaged in the Paraguayan Chaco Soybean Frontier

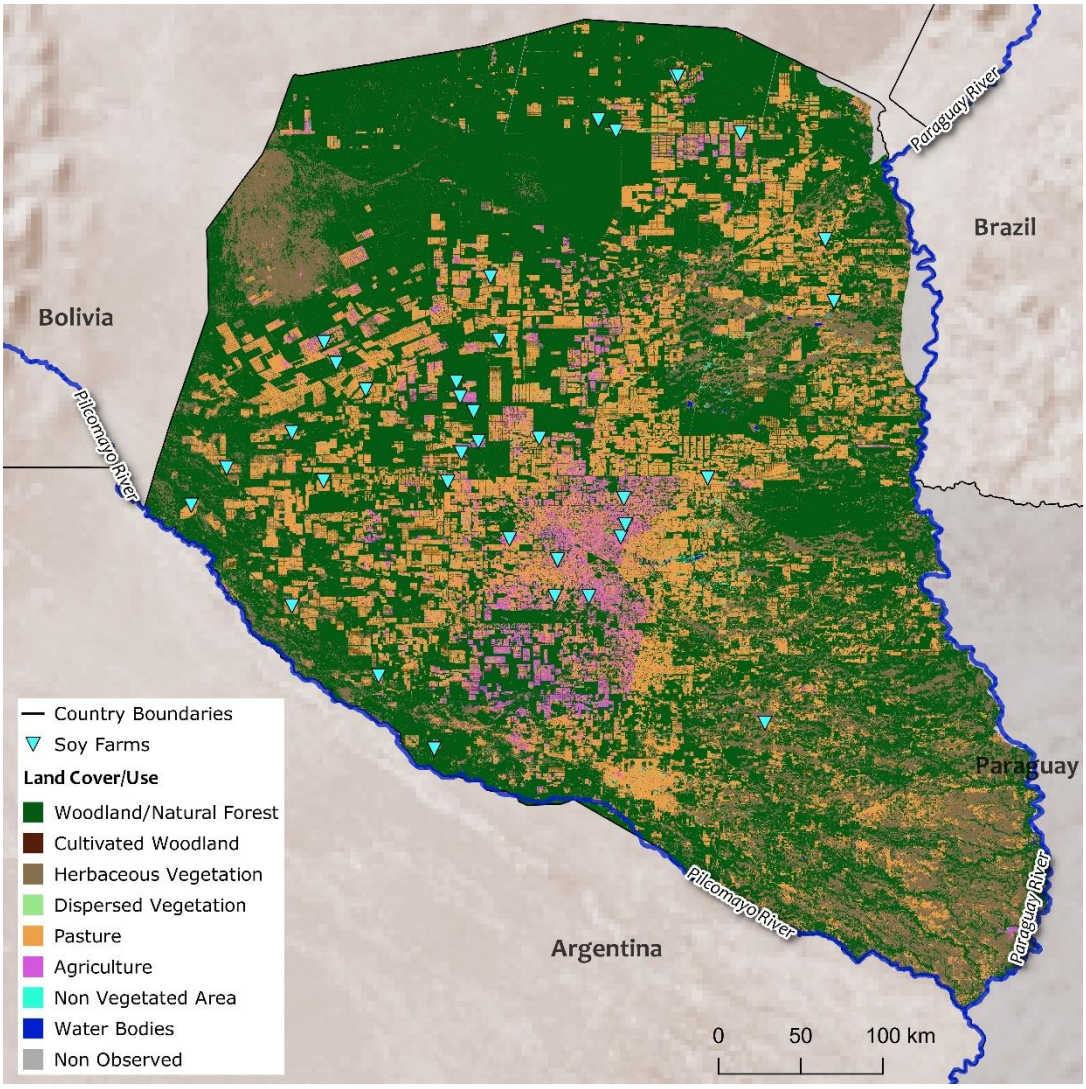
Actor Type	Actors / Actor Description
Large Scale Producers (over 500 Hectares) – actively export soybeans	CRESUD SA. (ARG), Carlos Casado (ARG), (formerly formed as joint venture "CRESCA SA"), Brasil Agro/Palmieras/Moroti (ARG/BRA), Faro Norte (PRY)
Medium Scale Producers (100-500 Hectares) – some export soybeans, others incorporate soybeans in cattle operation	Paraguayans (from Eastern Region), Mennonite/Paraguayans, Argentineans, Uruguayans, Brazilians, French.
Mennonite Producers (under 100 Hectares) – mostly to diversify cattle operations	Fernheim, Chortitzer, Neuland
Research and Development Production Plots – experiments for drought resistant soy genetics	CAPECO, USDA, University of Missouri, Chortitzer, Fernheim, Neuland
Government Organizations	MADES, INFONA, Municipality of Filadelfia, Government of Boquerón, USDA
NGO's / Intergovernmental Organizations	World Wildlife Fund (WWF), Guyra, United Nations Development Programme (UNDP), Birdlife International/Americas, World Conservation Society, Rainforest Foundation Norway, Federation for the Self-Determination of Indigenous Peoples (FAPI), Eco Pantanal, Paraguayan Federation of No-till Sustainable Agriculture (FEPECIDAS), Soladaridad, International Union for Conservation of Nature (IUCN),
Industry Groups	Rural Association of Paraguay (ARP), CAPECO, Agricultural Association of Agua Dulce (APAD), The Indigenous-Mennonite Cooperative Services Association (ASCIM), Assembly of Agricultural Producers for a Sustainable Chaco (APACS)

5 Observed soybean production locations based on soil types and land-cover in the Paraguayan Chaco*

Soil Type	Area		Number of soy farms	Forest Area	Forest Plantations Area	"Herbaceas" Area	Disperse Vegetation Area	Pasture Area
	km²	%		km²	km²	km²	km²	km²
Cambisols	8448.26	3.49	1	5566.13	0.05	871.01	0.63	1531.18
Luvisols	49378.36	20.38	14	28566.10	0.01	2301.86	2.53	16893.58
Regosols	66754.58	27.55	17	49551.47	0.12	4542.84	5.72	12196.97
Solonetz	84361.08	34.82	4	45070.77	77.37	20968.45	0.37	20292.65
Other	33256.08	13.75	0	16291.79	7.60	12656.88	3.04	4236.53

*Calculations based on Fig. 1 and Supplementary Online Material section 6

6 Location of recently observed soy production based on historical land cover map



Observed soy production on 2016 land-cover map provided by WWF/Guyra/DLR 2016.

7 Summary of data used in suitability map and driver analysis

Soybean Occurrence: Given the poor spatially explicit data available in the Paraguayan Chaco, as well as the nascent state at which soybean production in the region is currently in, we determined soybean occurrence based on field interviews and through information gathered via public, and invite-only, social media groups[1] created for soybean producers in the Chaco region. Studies based on remote sensing data Hansen and Potapov et al. (2013); MapBiomas Project Chaco (2019), are not able to distinguish between agricultural land-uses at the level of analyses needed to measure current soybean production levels. We assume that our study accounts for all soybean occurrence in the Paraguayan Chaco region based on information gathered in 2019, however, this analysis should be understood as a preliminary assessment, as there is no central database nor land-use maps that reflect official figures.

8 Other Data (socio-economic, land-use, environmental)

Land Cover Data: *MapBiomas Project Chaco (2019); Hansen (2018); WWF (2016)* Land cover data is based on data acquired from WWF Paraguay based historical land cover for the year 2016. There are 9 different classifications of land seen in supplementary online material section 6.

Land Price: Publicly available land price data is not available in Paraguay. An initial attempt using a combination of the Paraguayan Rural Association's analysis of sustainable development (2016), the Paraguayan Ministry of agriculture's assessment of land price based on payments to ecosystem services (2019), and the Paraguayan Rural Association's handbook on agricultural development published by MF economic consultant group UGP (2015) was initially attempted in the first model run. However, its low quality and low predictive power made us omit land price as a variable.

Infrastructure and Accessibility: Infrastructure data is based on an author modified version of DIVA-GIS transportation data available for Paraguay Hijmans, Guarino and Mathur (2012). Port data, and water body data is based on the Paraguayan administration of navigation and ports ITAIPU - ANNP (2017). These data were used, along with the previously mentioned land-cover data, to create maps of accessibility Schielein and Frey et al. (2021) to ports and cities, similar to Schielein, Ponzoni Frey and Miranda Arana (2017) and Frey and West et al. (2018). However, we selected cities in our study based on their relevance to the soybean industry in the Chaco region based on information gathered on field visits.

Climate Data: Climate data is based on the global WorldClim dataset, which looks at bio-climatic variables, precipitation, as well as temperature data Fick and Hijmans (2017). A first

9) The use of whatsapp, and facebook groups specific to the Paraguayan Chaco and/or soybean production in the region

model run showed that bioclim5 and bioclim2 were the most important ones in predicting soybean expansion, so we re-ran the model keeping only these two bioclimatic variables.

Soil Data: Soil data is based on an analysis by Paraguayan NGO Guyra, based on information obtained by the Paraguayan National Cadaster Service (SNC).

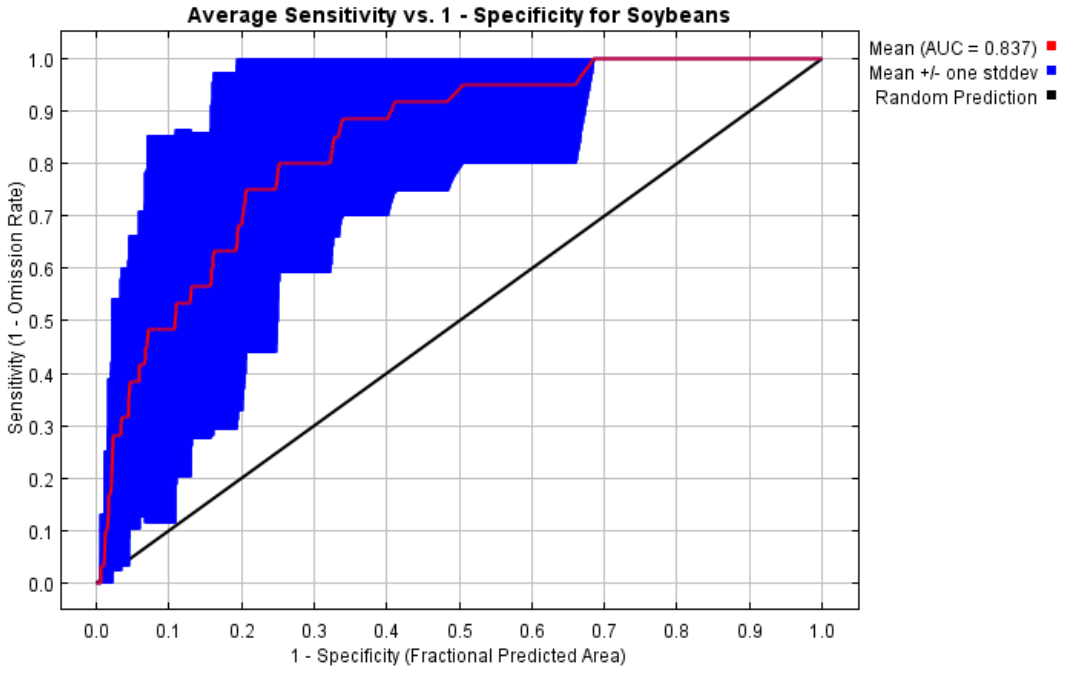
9 MaxEnt model

We implemented SDM based based on presence data using a Maximum Entropy approach Phillips, Anderson and Schapire (2006); Souza and Marco (2014); Frey and West et al. (2018) using the MaxEnt software version 3.3.3 (Princeton, USA) to calculate the probability and extent of soybean expansion in the Paraguayan Chaco, using a similar approach as Frey and West et al. (2018) which used the SDM framework and MaxEnt to project soybean expansion in Brazil. Other studies have used SDM frameworks to assess agricultural expansion dynamics Souza and Marco (2014); Amici and Marcantonio et al. (2017). The MaxEnt approach allows our analysis to incorporate novel soybean presence data collected during our fieldwork with additional continuous and categorical data using machine-learning algorithms to create a suitability map. This approach analyzes the biophysical and socio-economic variables (Table 1; further detailed in supplementary online material section 7 and 8) at the locations where soybean production has been identified to constrain the probability distribution of potential soybean production by maximizing entropy (uniformity) where soy occurrence is unknown. This information is then used to compute a probability distribution of soybean occurrence across the Paraguayan Chaco region[2]. Model performance can be measured by the rate of background pixels incorrectly classified as presences plotted against the rate of positive observations classified as positive by the model. This is a modified Receiver Operating Characteristic (ROC) curve based on presence-only data Phillips, Anderson and Schapire (2006), and the area under the curve (AUC) measures the probability that a randomly drawn pixel will have a higher predicted value than a randomly drawn background pixel Elith and H. Graham et al. (2006). An AUC of 0.5 means that the model does not predict better than a random distribution. An AUC >0.7 is considered to indicate good predictive power of the model. The 35 runs of the MaxEnt model variables using default settings, based on the data collected in our literature review and field work yielded results with an average AUC of (0.837) with a standard deviation ±0.123, demonstrating that the variable subsets included in the model yield similar results through each of the trials, indicating high predictive power in the model (supplementary online material section 10). The Jackknife test (supplementary online material section 11) disaggregates the individual variables and identifies each variables' respective impact in predicting which areas are most likely for soybean expansion to occur in the Paraguayan Chaco. The variables with the highest explanatory power are land-cover

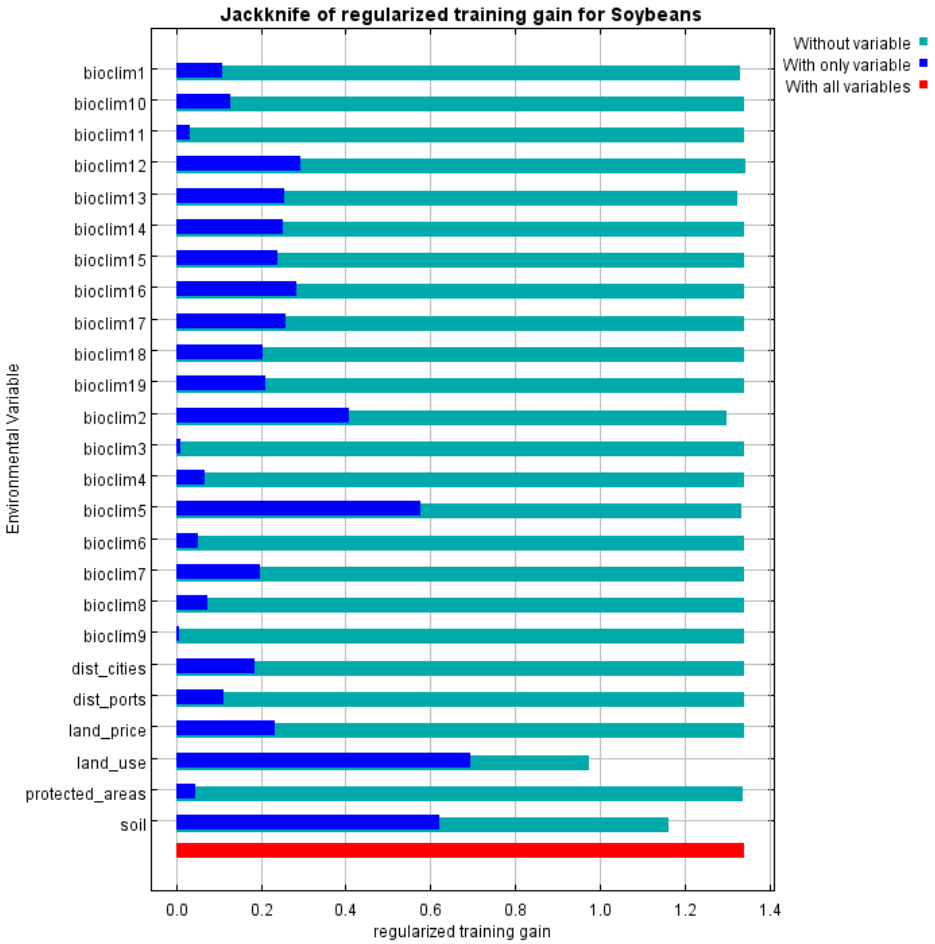
[2] A uniform probability distribution of soybean production across the region would be expected if no variables were known.

(land_use), followed by soil type (soil), maximum temperature during the warmest month (bioclim 5), and distance to cities (dist_cities). Mean diurnal range (bioclim 2) and distance to port (dist_ports) had moderate predictive power.

10 The area under the curve (AUC) of MaxEnt results



11 Jacknife sensitivity test results from MaxEnt analysis



**A list of indicators are listed in Table 1.*

12 Interview List

Interview 1: Ing. Carlos Passerieu – (Palmieras/Moroti) - Large-scale manager/producer
Interview 2: Dr. Egon Neufeld – (Faro Norte) - Large-scale manager/producer
Interview 3: Did not want to be identified by name (CRESCA) - Large-scale manager/producer
Interview 4: Ing. Jenny Dueck – (Chortitzer) - Producer/technical expert and agronomist
Interview 5: Jorge Martinez (UNDP) - Technical expert
Interview 6: Ing. Ramon Aguero (Palmieras) – Large-scale manager/Producer
Interview 7: Calixto Saguier (WWF Paraguay) - NGO Staff
Interview 8: Ing. Martin Mongelos (WWF Paraguay) - NGO Staff
Interview 9: Did not want to be identified by name (Producer, Central Chaco) - Small producer
Interview 10: Did not want to be identified by name (Chortitzer affiliated producer) - Medium producer
Interview 11: Atahualpa Ayala (Former Department of Cadaster / Independent Consultant) - Technical expert
Interview 12 Oscar Ferreiro (UNDP) - NGO Staff
Interview 13 Ing. Enrique Molas, (Sustainability Consultant) – Technical expert
Interview 14. Ing. Martin Cubilla (CAPECO) - Technical expert
Interview 15: Did not want to be identified by name (Producer central Chaco region) - Small producer
Interview 16: Did not want to be identified by name (Producer central Chaco region) - Medium producer
Interview 17: Hector Cristaldo (UGP) - President
Interview 18: Rosalia Goertzen (Fernheim Colony) - Technical expert
Interview 19: Oscar Rodas (UNDP) NGO staff
Interview 20: Marcos Glauser - Researcher
Interview 21: Did not want to be identified by name (Producer in Central Chaco) – Small producer
Interview 22: Did not want to be identified by name (Producer in Central Chaco) – Small producer
Interview 23: Did not want to be identified by name (Producer in Central Chaco) – Medium producer
Interview 24: Did not want to be identified by name (Cattle producer in Central Chaco) – Large scale producer
Interview 25: Fabiana Arévalos (Guyra) - Habitat and Landscape Program Coordinator