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Ecological interactions, feedbacks, thresholds and collapses in the Argentine Pampas in response to climate and farming during the last century

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Abstract

The Western Pampas consists of a large and complex sand dune system that originated during the last Pleistocene glaciations and was reworked during later semi-desertic episodes. Humans only colonized the region during the last century, but their action was powerful enough to produce two catastrophic events: one during the first half of the century, and the other one during the second half. Deforestation, over grazing, over cropping plus a non-suitable tillage technology in interaction with extremely dry and windy conditions of the 1930s and 1940s, caused a large dust-bowl episode that triggered severe dust storms, cattle mortality, crop failure, farmer bankruptcy and rural migration. During the second half of the century, improved rainfall conditions favored the conversion of abandoned lands into grazing lands and croplands. At the same time, recurrent episodes of flooding affected the area between 1970 and 2002, more drastically in the highly productive lowlands of the Río Quinto Watershed. The configuration of dunes with respect to the slope, and the lack of a suitable infrastructure, impeded water removal and favored its accumulation. High cultivation rates dramatically increased the severity of floods during such humid periods. The ecological catastrophes of the Western Pampas during the 20th century were the result of a complex interaction involving the geological configuration, climate variability and human intervention. Over cropping has probably surpassed critical ecological thresholds and this, in turn, triggered both the dust-bowl and the flooding events. On the other hand, natural feed-back mechanisms were probably activated allowing a later stabilization and recovery of the affected lands.

1. Introduction

Two recent ecological catastrophes that severely have affected the integrity of regional ecosystems in the Pampas can be explained by the aggressive human intervention during the last century (Viglizzo et al., 2001). The area has a relatively short farming history, since the Pampas remained as native grassland until the end of the 19th and the beginning of the 20th century. Then, lands were allocated in varying proportion to cattle and crop production under dryland conditions. Currently, a relatively small proportion (around 25%) of uncultivated land persists (Viglizzo et al., 2001). Most lands are devoted to grain crops (sunflower, maize, soybean and wheat), that rotate with annual forage crops (oat, triticale and rye) and perennial pastures (alfalfa and grasses) (Díaz Sorita et al., 2002). Even though cultivation intensity is still lower than in other regions of the Northern Hemisphere (Viglizzo et al., 2001), moderate soil degradation occurs all over the ecoregion (Solbrig and Viglizzo, 1999). Cattle production was a predominant activity during most of the 20th century, but crop production persistently increased since the 1960s, reaching a peak today (Viglizzo et al., 1997).

Recent results (Viglizzo et al., 2003) demonstrate that those changes were the cause of ecosystem disruption in the Pampas during the last century, probably affecting the provision of essential ecological services (like erosion control and water regulation) that are essential to prevent undesirable catastrophes. In this contribution, we try to explore and interpret the nature and the causes of two ecological catastrophes that dramatically undermined human well-being in the region.

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2. The Western Pampas

The Argentine Pampas (33–35°S, 62–64°W) is a wide plain of around 54 million hectares of fertile lands suitable for cattle and crop production (Hall et al., 1992; Viglizzo and Roberto, 1998). The biome is not homogeneous, since soil quality varies (Satorre, 2001) and rainfall declines from NE to SW. Using these patterns, the region can be divided into five agro-ecologically homogeneous areas (Fig. 1) as follows: Mesopotamian Pampas, Rolling Pampas, Western Pampas, Flooding Pampas and Southern Pampas. Rainfall regimes vary across time and space, causing cyclical drought and flood episodes that affect both crop and cattle production (Viglizzo et al., 1997).

In terms of ecological catastrophes, the Western Pampas offer two interesting case studies. The Western Pampas amounts around 16 million hectares, scattered across four Argentinian provinces (San Luis, Córdoba, La Pampa and Buenos Aires). This region, also known as Sandy Pampas, consists of a large and complex sand dunes system (Zárate, 2003) that corresponds to the Sand Sea of Iriondo (1990). This large sandy cover was generated during the last Pleistocene glaciations and was partially reworked during later desert and semi-desert episodes (Iriondo, 1999). Several significant climate changes, involving wet and dry periods, occurred during the last 200,000 yr (Carignano, 1999) resulting in a sequence of Upper Quaternary aeolian deposits interbedded with paleosoils (Carignano, 1999; Iriondo, 1999). Even though the primary transport of such materials has been caused by South–Southwesterly winds (Hall et al., 1992, Iriondo, 1999; Morrás, 1999; Zárate, 2003), fluvial transport might also have happened (Morrás, 1999). Late Pleistocene–Holocene deposits of variable thickness covered the region, and constituted the parent material of the modern cultivated soils (Zárate, 2003). These soils are sandy loam to sandy Mollisols, composed by very fine and fine silty sand, with minor clay, dominated by minerals of the Illite group (Iriondo, 1999). The topsoil is moderately acidic, with an organic matter content of about 30 mg g^{-1} (Hall et al., 1992).

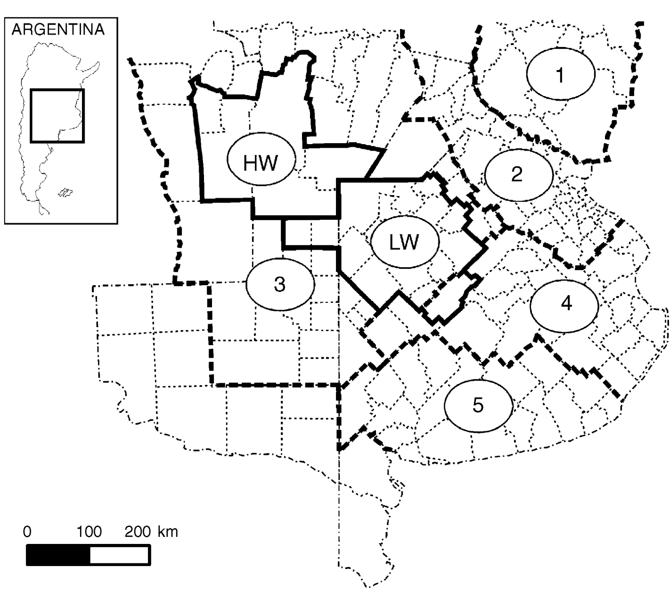

Fig. 1. Location of the Mesopotamian Pampas (1), Rolling Pampas (2), Western Pampas (3), Flooding Pampas (4) Southern Pampas (5); and the Higher (HW) and Lower (LW) Río Quinto Watershed. Lines represent Eco-regions boundaries (thick dashed line), Watershed boundaries (thick line), Provinces boundaries (thin dot–dashed line) and Districts (thin dashed line).

The climate of the Western Pampas is temperate with some continental characteristics (mean annual temperature ~16.2 °C). Wind is more intense (around 16.8 km h^{-1}) and more frequent (only 14% calm days) during the hottest season (Hall et al., 1992). During this period, aeolian erosion of soils is more frequent on sandy textured soils or on soils, which keep a poor plant residue cover after plowing. This is one area in the world where dust storms frequency is relatively high (from 30 to 100 days per year) and where wind-blown dust is common. Most rainfall occurs between October and April (from spring to fall), averaging around 900 mm yr^{-1} (Díaz Sorita et al., 1998).

The Río Quinto crosses the region to the Southeast along a complex alluvial belt bounded by a large deflation landform (Carignano, 1999), that shapes the Río Quinto Watershed (Fig. 1), which is characterized by an endorreic and poorly developed drainage system. The Eastern portion of the area, the Lower Río Quinto Watershed is a wide plain with temporary and permanent lagoons where severe flooding episodes occur in some years. The Western part, the Upper Watershed, on the other hand, is a less flood-prone area due to its topography, lower rainfall regime and permeable soils (Hall et al., 1992).

3. Interaction of geological, climate and human factors

Various authors have studied the rainfall process in the Pampas since the beginning of the 20th century (Hoffmann, 1988; Forte Lay and Falasca, 1991; López Gay et al., 1996; Viglizzo et al., 1997; Minetti and Vargas, 1997; Minetti et al., 2003). Despite the variability among ecoregions, regression analyses have shown a decline of precipitation all over the Pampas until the 1950s, and then an inversion of trends during the second half of the century.

In this study, climatic statistics from locations across the whole area were provided by the Office of Meteorological Statistics. Additionally, records on land use from six national agricultural censuses and 32 annual agricultural surveys, obtained from the Argentine Secretary of Agriculture, were analyzed. Trends in rainfall, wind speed and cultivation were analyzed through simple quadratic regression models.

3.1. First collapse: the dust-bowl

Around the 1930s and the 1940s, rainfall in the whole area diminished by 200 mm on average, and isohyets showed an eastward displacement. At the same time, wind speed and frequency increased (Fig. 2b), triggering severe episodes of soil erosion (Bernardos et al., 2001). The process was driven and enforced through an unsound colonization program that started at the end of the 19th century. Deforestation, over grazing, over cropping plus a non-suitable tillage technology interacted with the predominantly dry and windy conditions producing devastating results (the Pampas' dust-bowl). Such interaction had led, since the beginning of the 1930s, to severe dust storms, cattle mortality, crop failure, farmer bankruptcy and rural migration (Hall et al., 1992; Solbrig. and Viglizzo, 1999; Zarrilli, 1999; Rojas, 2001). Probably, this episode represented the first large ecological catastrophe triggered by a negative interaction between climate and humans in the Pampas.

Old maps show the extensive distribution of sand dunes across the region, demonstrating the magnitude and severity of the event (Fig. 3a). Erosion had negative effects at the field level, and also impacted on larger areas outside the field. The model reconstruction of erosion in the Western Pampas provided by Bernardos et al. (2001) shows the impact of this event. Erosion peaks were extremely severe during the 1930s and 1940s (Fig. 4a), surpassing the high erosion risk category of more than 33 metric tons ha^{-1} (Agriculture and Agri-Food Canada, 2000).

Looking at a synthesis, a hypothetical model is proposed to describe and interpret the ecological dynamics of the area during this period (Fig. 5a). Apparently, initial conditions (severe winds, low rainfall, over cropping and over grazing) triggered a positive feedback that moved the system away from its original state. Wind erosion and dune formation were the external signals of the ecological collapse that caused in turn a socio-economic collapse (Zarrilli, 1999; Rojas, 2001). After bankruptcy, many families abandoned their farms and moved to other areas. The lower pressure over the environment during the following decades triggered a stabilizing negative feedback that was boosted by improved climatic conditions and technologies. At that time, a new equilibrium state was established.

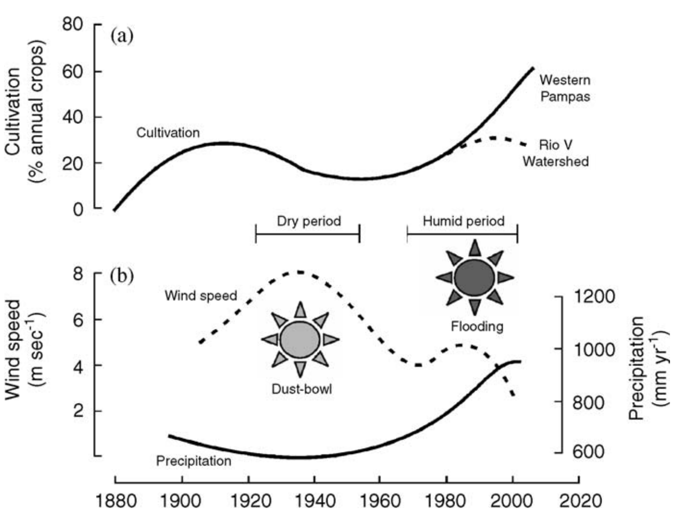

Fig. 2. Cultivation (% of cropped land), Wind Speed (m s^{-1}) and Precipitation (mm yr^{-1}) tendencies over time in the Western Pampas. Dashed line in part (a) represents the Río Quinto Watershed case. Lines are second degree regression models. Stars represent the timing of the two collapses.

3.2. Second collapse: floods

During the second half of the century, improved rainfall conditions (westward displacement of isohyets) favored the conversion of abandoned lands into grazing lands and croplands. After the dust-bowl, a long stagnation period that lasted until the 1960s was followed by a quick agro-ecological recovery. Viglizzo et al. (1997) found a significant correlation between rainfall variability and the percentage of croplands for the humid and subhumid districts of the Pampas. According to them, a positive interaction between rainfall and technology was the main factor explaining land use recovering in this area. New legislation, institutions and technology, plus the reversion to a humid phase in the climate cycle, favored a rapid re-flowering of farming, especially in the Western Pampas.

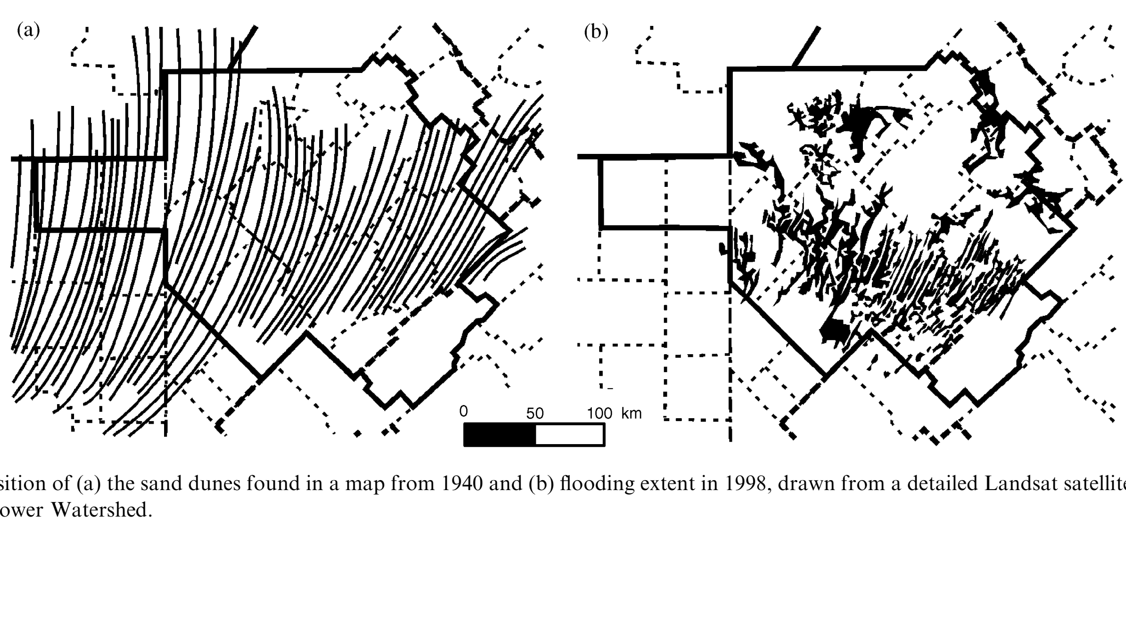

Fig. 3. Disposition of (a) the sand dunes found in a map from 1940 and (b) flooding extent in 1998, drawn from a detailed Landsat satellite image, on the Río Quinto Lower Watershed.

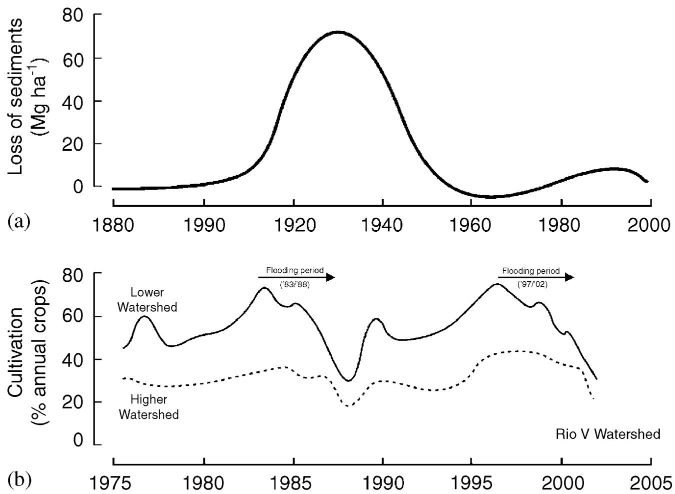

Fig. 4. (a) Reconstruction of soil erosion in the Western Pampas through the EPIC model (Bernardos et al., 2001) and (b) cultivation intensity (% of cropped land) over time in the Lower and Higher Río Quinto Watershed. Lines are rough estimates of the trends.

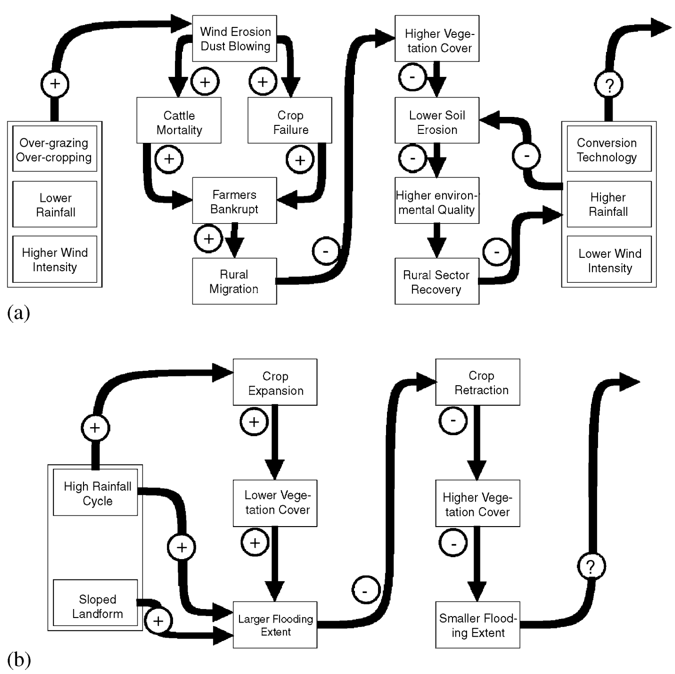

Fig. 5. Hypothetical model to interpret the ecological changes in the Western Pampas during the dust-bowl (a) and the episodes of flooding of the Río Quinto Watershed (b), and their related collapses. (+) and (–) symbols represent positive and negative feedbacks, respectively.

As a result of the noticeable increase in rainfall, recurrent episodes of flooding affected the area after the 1970s, more drastically in the highly productive lowlands of the Río Quinto Watershed (Fig. 1). This closed basin, which suffered from the successive alternation of cultivation and flooding cycles (Minetti and Vargas, 1997; Minetti et al., 2003), extends over 12.4 million hectares. The highly productive Low Watershed, which extends over 5.6 million hectares, has been the most affected area due to the removal of prime agricultural lands from farming. As can be seen in Fig. 2a, the percentage of croplands in the Watershed shows a functional dissociation from the Western Pampas during the humid period. Presumably, this watershed behaves like a system which has self-regulating rules that need to be elucidated.

A map, drawn from a detailed satellite image of the Low Watershed during one of the flooding periods, shows the magnitude of the event (Fig. 3b). As can be appreciated in the image, the system of dunes (Fig. 3a), generated in ancient times and transported by wind during the dust-bowl disturbance (Zarrilli, 1999), is aligned at right angles with respect to the slope, making difficult the natural evacuation of water and favoring flood spreading. This process was also enforced by the lack of infrastructure to remove water excess (e.g. drainage and channel systems).

A more detailed analysis of cultivation in the Low Watershed during the last 32 yr (Fig. 4b) suggests that some upper and lower thresholds might be triggering negative feedback mechanisms that control and self-regulate the functional behavior of the system. Upper thresholds might be reflecting a natural response of the watershed system to remove crops through flooding and avoid crop overloading. Lower thresholds, on the other hand, might be reflecting the human response to increase cultivation once local conditions have improved. So, cultivation might be moving within a self-regulation range that oscillates between 20% and 70% of crops over the total area.

This behavior can be better described through a hypothetical model that shows internal and external drivers, interactions and feedbacks that aim to explain the alternation of flooding and cultivation cycles in the Low Watershed (Fig. 5b). High precipitations, geological landforms, and heavy cultivation have presumably triggered positive feedbacks that resulted in large flooding episodes. After those events, the abandonment of annual cultivation and the growth of perennial vegetation would have stabilized the system. A conceptual explanation to this phenomenon can be extracted from the ecological theory. Water runoff reaches a minimum rate and infiltration maximizes under natural conditions, in which plant weight and plant cover per unit of area is high. The process is inverted when the landscape is transformed by cultivation and plant weight and plant cover decrease. Then, the severity of floods seems to depend on critical thresholds that are surpassed when vegetation is sparse and bare soil predominates during some periods within the farming year.

A large disruption of farming activities, an alteration of agricultural plans and a big socio-economic crisis have been the consequences of this second and opposite ecological collapse in the region (La Nación, 1987). Within one century, the Western Pampas passed from a very dry period with active soil degradation by wind erosion to a period of hydrological excess with severe floods (Minetti and Vargas, 1997). The dust-bowl and the flooding collapses have clearly been strengthened by human intervention. As a consequence, the quality of the rural environment has greatly varied along the 20th century.

4. Conclusions

Some conclusions about the functioning of the Western Pampas in relation to climate and human disturbances can be drawn:

The ecological behavior of the Argentine Pampas during the 20th century was the consequence of a complex interaction among geological-, climate- and human-dependent factors. Two devastating ecological events (dust-bowl and floods) that resulted from this interaction were the causes of two opposite catastrophes that deeply affected human well-being in the region at different times during the century.

We hypothesized that over cropping (a human-dependent factor) has probably surpassed critical ecological thresholds, and this in turn has triggered both dramatic events. However, such events have probably activated feedback mechanisms that in turn allowed a later stabilization and recovery of the affected ecosystems. More detailed information and new analyses are needed to confirm this hypothesis.

The Río Quinto Watershed is a closed basin that behaves, during humid periods, like an integrated system that dissociates from the rest of the Western Pampas. It responds to self-regulation rules that control the hydrological dynamics and result in flooding and cultivation cycles. In this case, self-regulating mechanisms involve interacting physical and anthropogenic factors, thresholds and feedbacks that operate within and across a set of hierarchical nested scales. While it is unlikely that a second dust-bowl episode can occur again under the current technological context, flooding episodes might replicate many times unless a broad scale and long-term land-use strategy is undertaken, especially in the Low Río Quinto Watershed.

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