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# A long-term sustainability assessment of an Argentinian agricultural system based on emergy synthesis

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ABSTRACT

By tracking the different flows of emergy (the total amount of solar energy that was directly or indirectly required in a production process) it is possible to account for all environmental work previously involved in generating a resource, product or service. This donor-side perspective for environmental assessment has the advantage over usual economic and energy analysis in the ability to value renewable and non-renewable environmental resource inputs both from the economy (purchased resources) and from nature (free resources) and compute their values on a common basis. On this basis, this paper presents the use of emergy synthesis on three cropping systems of the Pampa Region (Argentina) with the aim of evaluating the long-term trends (1984–2010) in emergy use and the effect of the adoption of new technologies in the study area. The cropping systems evaluated were wheat/soybean double cropping (W/S); maize (M), and spring soybean (S). Results form the emergy synthesis showed that the cropping systems studied were not only more productive but also more efficient over time. The range of the observed values for the emergy yield ratio (EYR) were 1.77–5.59, proving that the three cropping systems are considerably supported by renewable and locally available resources. The environmental load ratio (ELR) that represents the ratio between non-renewable and renewable resource inputs ranged between 0.3 and 1.43, a significant lower range compared to other extensive cropping systems. However, when inspecting the temporal dynamics of the emergy indicators, M and W/S showed a statistically significant optimum behavior, with the most favorable values just before the use of a more intensive cropping management represented by the use of genetically modified cultivars, the no-tillage adoption and the more frequent use of fertilizers at higher doses. By the time of these adoptions, both the EYR and ELR showed a breakpoint in their temporal dynamic, exhibiting a negative slope during the last years of the time series. Although the observed ranges of the emergy indicators can place these production systems among the most efficient and with the lower environmental impact, the negative trend in the emergy indicators shown in recent years constitutes a risky scenario in terms long-term sustainability.



## 1. Introduction

Agricultural ecosystems are natural systems artificially modified in order to obtain a product that generates a profit. However, in the last decades it emerged the idea of a trade-off between productivity-enhancing technical change (i.e. agricultural intensification) and the maintenance of ecosystem functions (i.e. ecosystem services) (Ruttan, 1994). Consequently, it led to a demand of analytic tools that can measure progress toward a broad range of social, environmental and economic goals (Reed et al., 2006). The use of energy can be used as an indicator of both structural and functional integrity in agro-ecosystems. This claim is based on the property of agricultural systems, like any biological system, to be subject to the basic laws of physics, such as energy exchange and the resulting thermodynamic balances (Bakshi, 2002).

Emergy analysis methodology, also called emergy synthesis, quantifies the consumption of goods and ecological and economic services that were used during a production process (Brown and Ulgiati, 2004). Emergy is defined as the total amount of available energy of one kind that is directly or indirectly required to make a product or service (Christensen, 1994). Originally proposed by Odum (1996) for system analysis, it allows direct comparison of biophysical flows in common units (i.e. emergy flow). Through a series of indicators, the methodology assesses the performance of a production system in terms of efficiency and intensity in the use of resources from nature and inputs from the economic system,

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from the objective perspective of thermodynamics. In particular, the assessment of system changes over time, in terms of sustainability goals, could be achieved by relating both the trend in natural resource (environment) and input purchased (economy) consumption of resources and inputs made (from the environment and the economy) during long-term time series. Several emergy evaluations were made on ecosystems all over the world, including agricultural systems (Agostinho et al., 2008, 2010; Cohen et al., 2006; Chen et al., 2006; de Barros et al., 2009; Ferreira, 2006; Marchettini et al., 2003; Martin et al., 2006; Rótolo et al., 2007; Rydberg and Haden, 2006). During the last years, the emergy use has received considerable attention (Franzese et al., 2014). However, data about long-term analysis of emergy flows in the recent literature are scarce (Chen and Chen, 2007; Lei and Wang, 2008; Ulgiati et al., 2011a).

In recent decades, the Pampa Region (Argentina) was subject to a process of geographical expansion and intensification of crop production (i.e. higher yields), as determined by the adoption of no-tillage system (Diaz-Zorita et al., 2002), the increase in input use (e.g. pesticides and fertilizers), the development of high-yielding cultivars genetically modified for resisting certain pests and herbicides (Trigo and Cap, 2003), and technological adjustments in crop management (Manuel-Navarrete et al., 2009a; Viglizzo et al., 2003). These changes has risen some issues regarding sustainability; among these are concerns that sustainability may be hampered by uncertainties and risks related to the intensification of natural resource and purchased inputs for increasing crop productivity (Viglizzo and Frank, 2006). Therefore, consequences for sustainability are still highly disputed (Manuel-Navarrete et al., 2009b). The objective is to assess the performance of a typical agroecosystem from the Pampa Region (Argentina) using an emergy analysis, in order to link long-term trends in both ecological and economical productivity and efficiency to the recent technological changes adopted in the studied area.

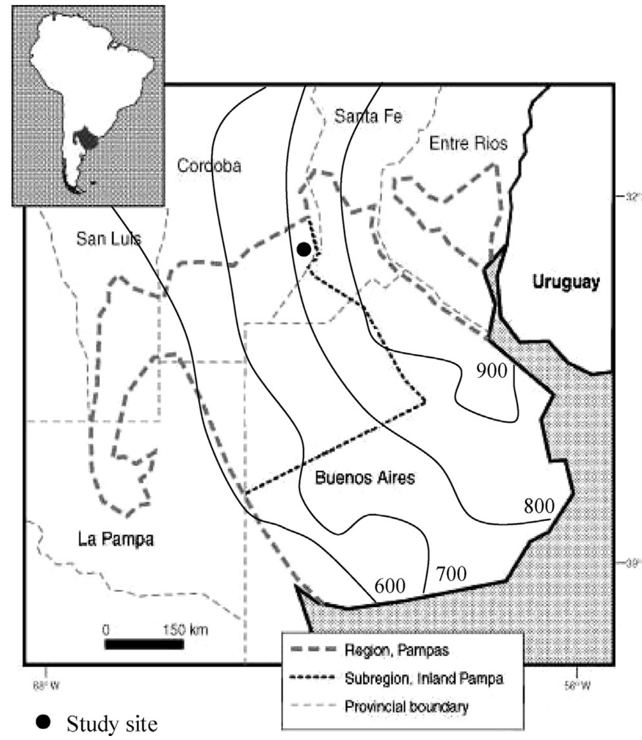
## 2. Materials and methods

### 2.1. Site description

The agro-ecosystem used as a case study in this work is located in the Inland Pampa (Argentina). The Inland Pampa (Map 1) is a sub region of a fertile plain originally covered by grasslands, which during the 1900s and 2000s was transformed into an agricultural land mosaic by grazing and farming activities (Soriano et al., 1991). However, since 1990 the traditional mixed grazing–cropping systems were being replaced by permanent agriculture. The most frequently cropped soils in the region are Mollisols, developed from eolian sediments of the Pleistocene era, with dominantly udic and thermic water and temperature regimes, respectively (Moscatelli et al., 1980). Average annual rainfall decreases from about 900 mm in the east to 750 mm in the west part of the study area (Soriano et al., 1991).

### 2.2. Cropping systems

Data analyzed come from an experimental farm located in INTA Marcos Juárez (32°41′ S, 62°09′ W), in a long-term experiment that was devoted exclusively to agricultural production since 1975. The soil at this location is a silt loam, a typic Argiudol, Marcos Juárez Series. The soil organic matter content was 2.5–3.5% and the pH was 6.5. Daily weather data, including solar radiation, and precipitation, were obtained from the meteorological station at this site. The long-term crop rotation experiment included among others, the following four rotation sequences: soybean/soybean, soybean/wheat, soybean/maize, and soybean/maize/wheat. We restricted our analysis to crop-specie level by analyzing the long-term emergy performance of (1) wheat/soybean double cropping (W/S); (2) maize (M), and spring soybean (S). We used both management and environmental data, along with the crop yield for a period of 27 years (1984–2010; for spring soybean the time range was 1984–2007). The experiment was designed as a duplicate, so that in each season, each crop stage of the rotation was being grown. The experimental design was a randomized block with two replications. Plots were 90-m long and 14.5-m wide. During the entire long-term period, the agronomic decisions (i.e. selection of genotypes, fertilizer management, pest control, etc.) were representative of the changes in the cropping systems of the studied area. These system modifications were mainly represented by three major technological changes: (1) the adoption of no-tillage system (NT); (2) the adoption of genetically modified organisms (GMO); and (3) the start of systematic fertilization (F). No-tillage minimizes soil mechanical disturbance and consequently reducing soil erosion and carbon losses processes, as it leaves a greater percentage of soil covered with plant residues (Lal et al., 1999). The GMO adoption started on 1996, when it was released the first GMO crop introduced in agriculture Argentina, the glyphosate-tolerant soybeans (RR) (Trigo and Cap, 2003). The cultivation of RR soybeans, along with transgenic corn hybrids resistant to Lepidoptera (released in 1998) showed an explosive adoption rate among pampean farmers and it is estimated that 99% of soybeans and 83% of maize crops in Argentina are GMO (Burachik, 2010). Regarding the fertilizer use, the natural high fertility of pampean soils and unfavorable fertilizer:grain price relationships prevented widespread chemical fertilization until the 1990s, when a new scheme of continuous agriculture (as opposed to earlier pasture/crop rotations) with the systematic use of fertilizers at higher rates (Portela et al., 2006; Viglizzo et al., 2011). All these system changes represented shifts in emergy flows that can be properly analyzed by using the emergy analysis in order to highlight possible long-term trends or




**Map 1.** Location of the study site (Marcos Juarez, Córdoba) within the Inland Pampa subregion and the Pampa region boundaries. Thin contour lines are isohyets (mm per year).
*Source*: Adapted from Ghersa et al. (2002) and Viglizzo et al. (2004).