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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.

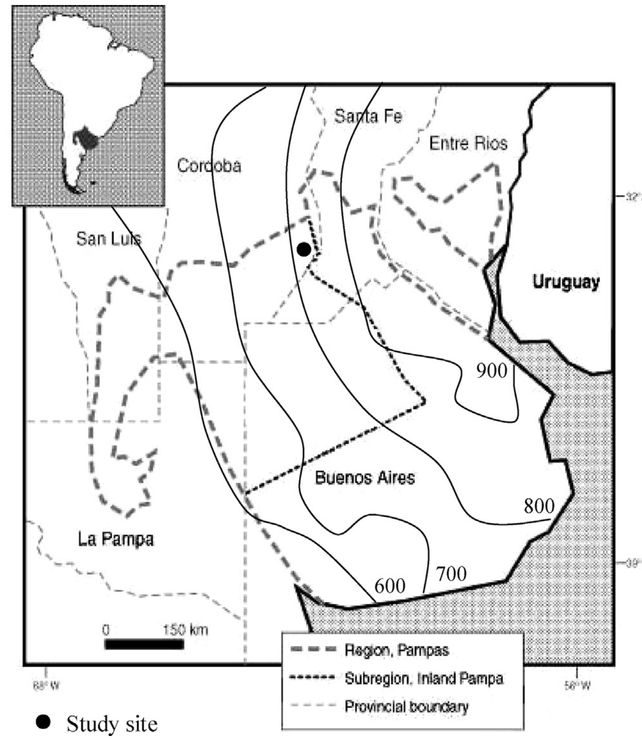
2. Materials and methods

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



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).

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 cycles regarding the emergy use and the sustainability of resource use.

2.3. Emergy analysis

A typical diagram of the crop production system is presented in Fig. 1. The diagram illustrates the boundary, main components and interactions. Inputs of the crop production system can be categorized into four types as shown in that diagram: (1) local renewable resources (R), such as sunlight, rain, wind and earth circle, (2) local non-renewable resources (NR), such as net loss of topsoil, (3) purchased materials (M), such as mechanical equipments, purchased diesel, chemical fertilizers, seeds and pesticides, and (4) purchased services (S), such as labor, and technical management (Tao et al., 2013). This categorization is the based for calculating the relationships (i.e. emergy-based indicators) among emergy flows. For the emergy calculations based on the emergy evaluation tables, the materials and services were not totally considered as non-renewable resources (Cavalett et al., 2006; Ulgiati et al., 1994). The classification of emergy flows to assess the partial renewability of materials and services are calculated as follows (Cavalett et al., 2006).

$$M = M_R + M_N \quad (1)$$

where M_R represents the renewable materials from natural origin; and M_N are minerals, chemicals, steel, and fuel.

$$S = S_R + S_N \quad (2)$$

where S_R represents the manpower supported by renewable sources; and S_N are other services (external), taxes, and insurance. Details about the items associated with each kind of flux (R, NR, M, S) along with the data sources and the calculation procedure can be found in Appendix A. We have included the emergy evaluation table for one year and cropping system; in order illustrate the table structure, the emergy calculations and data sources. The other tables calculated (75) for the combination of year and cropping systems has the same structure and data sources. The common measure for assessing the available energy is the solar insolation emergy with the unit solar emjoules (sej), and the final value can be calculated whether the physical measure were expressed in energy, mass or money flows (Brown and Ulgiati, 1997; Tilley and Swank, 2003):

$$\text{Solaremergyflow}(\text{sej yr}^{-1}) = \text{solartransformity}(\text{sej J}^{-1}) \times \text{energyflow}(\text{J yr}^{-1}) \quad (3)$$

$$\text{Solaremergyflow}(\text{sej yr}^{-1}) = \text{specificsolaremergy}(\text{sej g}^{-1}) \times \text{massflow}(\text{g yr}^{-1}) \quad (4)$$

$$\text{Solaremergyflow}(\text{sej yr}^{-1}) = \text{emergy-to-moneyratio}(\text{sej \$}^{-1}) \times \text{massflow}(\text{\$ yr}^{-1}) \quad (5)$$

The emergy accounting procedure is organized through emergy evaluation tables that describe both the input level in physical units (i.e. Joules, kilograms, $) and the emergy per unit value (i.e. the first terms in Eqs. (1)–(3)). The emergy per unit value (also caller transformity) has been calculated for a wide variety of energy forms, resources, commodities, and services (Brandt-Williams, 2001; Brown and Bardi, 2001; Odum et al., 2000b). The emergy per unit for labor and services was based on the emergy person^{-1} ratio and emergy-to-money ratio that was reported for the economy of Argentina during 1996 (Ferreira, 2006).

2.3.1. Emergy-based indicators

This paper selected a basic set of emergy-based indicators for assessing the system performance. These indicators are related to efficiency; yield; environmental load; investment return; and sustainability level. The emergy indicators (Brown and Ulgiati, 1997; Odum, 1996) were slightly modified in order to evaluate the emergy use by considering renewability of each one of the resources used (Cavalett et al., 2006). On the bases of the fluxes described in Fig. 1, a series of system indicators are explained and calculated as follows:

$$T = \frac{U}{\text{Crop yield}} \quad (6)$$

Transformity (T) is the ratio of total emergy input U (sej ha^{-1}) divided by the energy contained in the crop yield (J ha^{-1}). It is a measure of the efficiency in the use of emergy to obtain the crop production.

$$\text{NR}_f = \frac{NR}{NR + R} \quad (7)$$

The free local non-renewable resource fraction (NR_f) is defined as the ratio of local non-renewable emergy to the free environmental emergy inputs.

$$\text{EYR} = \frac{U}{(M_N + S_N)} \quad (8)$$

This indicator is calculated as the ratio of the emergy output (U) divided by the non-renewable emergy input as feedback from the outside economy. The higher the value, the greater the return obtained per unit of emergy invested, indicating the potential contribution that is made to the main economic system from the exploitation of local resources.

$$\text{ELR} = \frac{NR + M_N + S_N}{R + M_R + S_R} \quad (9)$$

This indicator shows the ratio of the non-renewable emergy flows to renewable emergy flows, indicating the load of the environment generated by human-dominated non-renewable flows. The lower the ratio, the lower the stress to the environment.

$$\text{ESI} = \frac{\text{EYR}}{\text{ELR}} \quad (10)$$

The Emergy Sustainability Index (ESI) is defined as the ratio of the EYR to the ELR and it relates the yield to the emergy intensity of the activity. It shows the potential contribution to the economic system per unit pressure on the local system. Among the former 5 indicators, NR_f is newly added indicators for this study compared to the other emergy conventional indicators. This new indicator is meaningful for this study, and for similar studies where the use of non-renewable free resources could be important, as it reflects the soil use intensity (through the soil erosion cost), one main local free resource that supports the productivity of cropping systems. For a comprehensive clarification of the emergy accounting procedures for different systems as well as a expanded discussion of the meaning of emergy indicators, the reader is referred to (Brown and Ulgiati, 2004; Hau and Bakshi, 2004; Odum, 1996; Odum et al., 2000a).

2.4. Data analysis

In order to assess significant temporal trends in emergy-based indicators, piecewise linear regressions were fitted to the data. We used data annual-based data from 1984 to 2010 for wheat/soybean double cropping (W/S) and maize (M) and 1984–2008 for spring

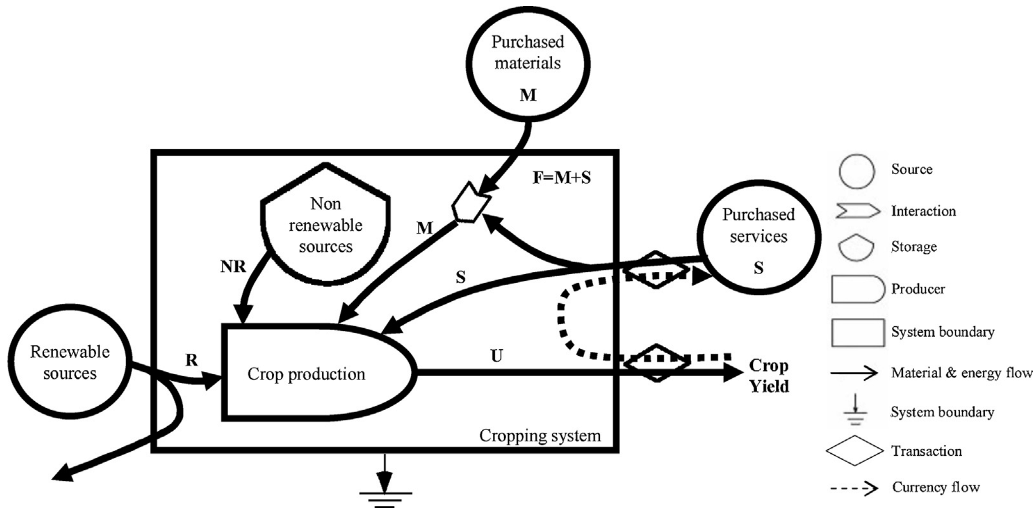


Fig. 1. Diagram of emergy flows for the cropping system analyzed (adapted from Rótolo et al., 2007 and Tao et al., 2013). U = total emergy; R = renewable sources; NR = non-renewable sources; P = purchased goods; S = labor and services; F = sum of imported emergy ($P+S$). P and S flows were not totally considered as non-renewable resources, by estimating their partial renewability (see text for details).

soybean (S). One or more of the following equations were fit to the data (Harper et al., 2005):

(a) Linear regression

$$y = b_0 + b_1 x \tag{11}$$

(b) Two-piece linear regression

If $x < t_1$

then $y = b_0 + b_1 x$, if $x \geq t_1$

$$\text{then } y = b_0 + (b_0 - b_1)t_1 + b_2 x \tag{12}$$

(c) Three-piece linear regression

If $x < t_1$ then $y = b_0 + b_1 x$, if $x \geq t_1$

then $y = b_0 + (b_0 - b_1)t_1 + b_2 x$, if $x \geq t_2$

$$\text{then } y = b_0 + (b_1 - b_2)t_1 + (b_2 - b_3)t_2 + b_3 x \tag{13}$$

where x is time, t_1 and t_2 are the breakpoints, b_0 is the y-intercept and b_1, b_2 and b_3 are the slopes for the first, second and third segments. Two and three-piece regressions were non-linear and involved parameter estimation conducted using non-linear estimation procedure of Statistica v.8 through using the quasi-Newton optimization method (StatSoft, 2007). Since the final parameter values were dependent on initial parameters, the data were first assessed visually to determine whether two or three-piece segmented linear regressions would be appropriate, to estimate parameters and determine whether any data could be considered outliers. Regressions were considered significant if the 95% confidence intervals of one or more consecutive slopes did not contain zero ($P < 0.05$). For piecewise regressions with two or more pieces, F and R^2 statistics were not available; therefore estimates were calculated:

$$R^2 = 1 - \frac{SS_{res}}{SS_Y} \tag{14}$$

$$F = \frac{MS_{reg}}{MS_{res}} \tag{15}$$

where SS_{res} and SS_Y are the residual and corrected total sum of squares, and MS_{reg} and MS_{res} the regression and residual mean squares, respectively (Harper et al., 2005). In order to test if the technological changes (the adoption of NT, GMO and F) were useful for improving the regression models, we also assessed if the regression breakpoints fell outside the time range of technological adoptions. Thus, the identification of the individual effect of each technology adoption may be evident from the degree of overlap between the time of adoption and statistically adjusted breakpoints. For further details about the piecewise regression assumptions ante significance test see (Harper et al., 2005; Toms and Lesperance, 2003).

3. Results

The cropping systems analyzed showed a significant increase in crop productivity during the period analyzed (Fig. 2). However, this pattern was only related to agricultural management changes (i.e. no-tillage, genetically modified crops adoption and systematic fertilization) in the double cropping wheat/soybean (W/S), whereas both maize (M) and spring soybean (S) showed a linear increase in crop yield (Fig. 2). Transformity (T) measures how much emergy is taken to generate one unit of output, and it indicated the emergy efficiency of crop production. Results from transformity linear regressions showed that cropping systems were not only more productive but also more efficient over time (Fig. 3) as the lower the transformity, the lower the need for environmental support to the process of crop production. However, this pattern was not the same for all the three cropping system analyzed. Particularly, maize (the higher-yielding crop), exhibited a plateau of transformity (Fig. 3) at the lowest recorded values (ca. 10,000 sej/J). This result would indicate that the system has reached a limit on emergy efficiency in agreement with the adoption of both genetically modified crops (GMC) and the start of systematic fertilization (F). The analysis of the different emergy sources showed the reduction of free local non-renewable resource fraction in all the cropping systems (Fig. 4). Results showed a remarkable drop in NR_f, from an average value of ca. 0.20 to an average value of 0.05 (Fig. 4). The bilinear regression models were highly significant, and showed a stabilization breakpoint, very close to the no-tillage adoption in the W/S cropping system (Fig. 4). Regarding the emergy fraction provided by the economic subsystem, in both W/S and M the use of purchased inputs decreased since the beginning of the time series

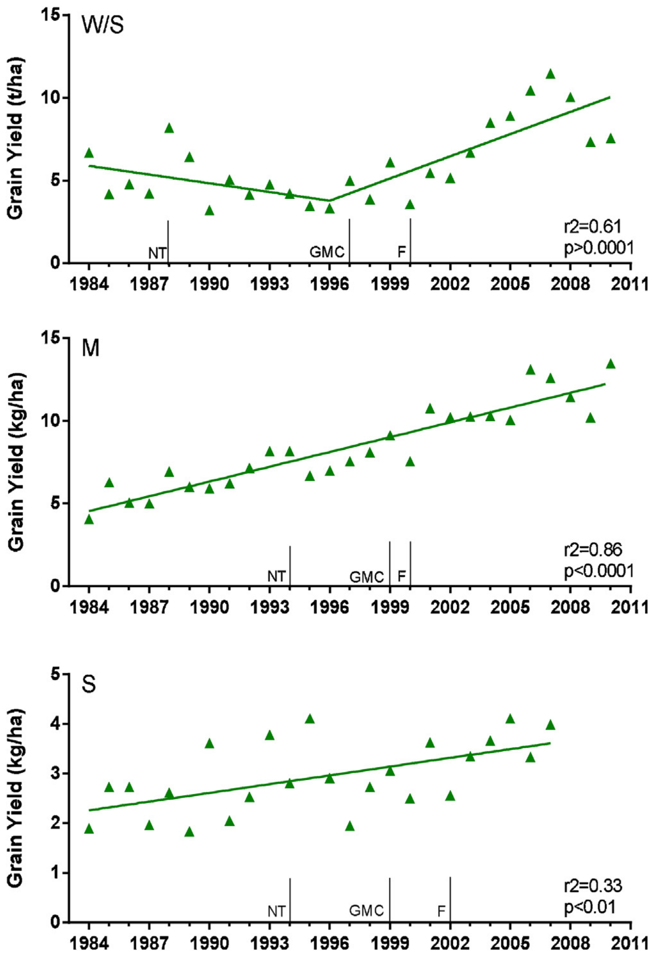


Fig. 2. Long-term changes of grain yield from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied (note the differences in the *y*-axis scale). Vectors in year axis indicate the adoption of no-tillage (NT), genetically modified organisms (GMC) and fertilization (*F*).

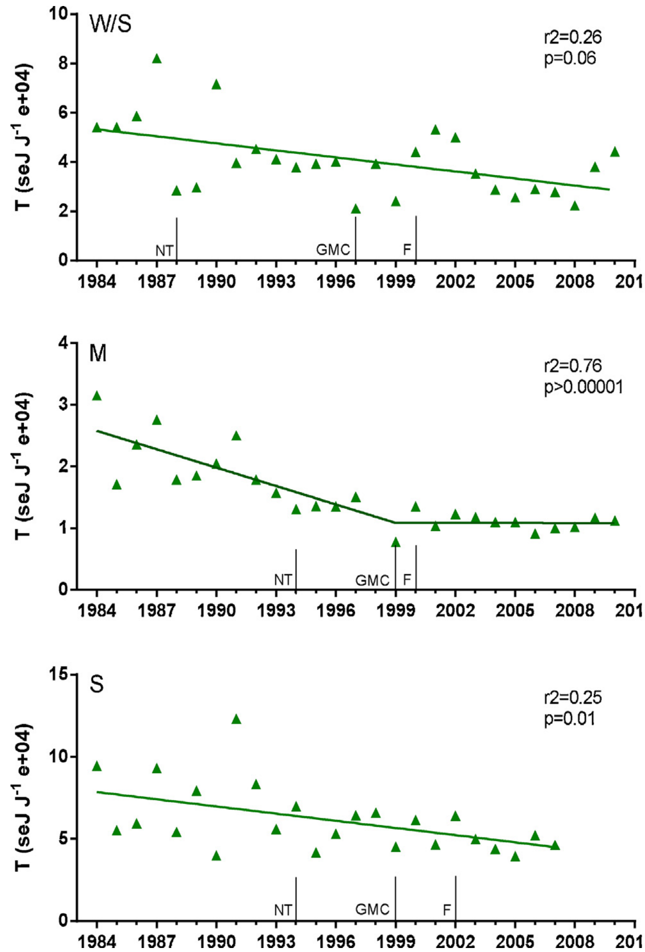


Fig. 3. Long-term changes of transformity (*T*) from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied (note the differences in the *y*-axis scale). Vectors in year axis indicate the adoption of no-tillage (NT), genetically modified organisms (GMC) and fertilization (*F*).

until the mid-90s, and from there it kept increasing until the last period (Fig. 5). In this case, the breakpoint between negative and positive linear trend of emergy consumed from purchased inputs were clearly linked to GMC and F adoptions (Fig. 5). Oppositely, the spring soybean (S) cropping system did not show a significant time trend during the time analyzed. Results from calculations of the EYR emergy indicator during the studied period showed that EYR values were regularly above the threshold line of EYR = 2, the threshold equal emergy contribution from economy and nature (Fig. 6): However, the EYR regression models showed a positive linear trend in emergy return until the adoption of the modern technologies in both W/S and M cropping systems. After this breakpoint, the negative slope described the decreasing trend in emergy return with values close to the EYR = 2 threshold by the end of the time series. The environmental load rate from the cropping systems (ELR) also showed a bilinear pattern, with a breakpoint showing a shift in linear relationship with time (Fig. 7). The minimum in the significant regression models (only W/S and M) was detected by 1994 as the ELR was ca. 0.5 for both cropping systems. The GMC and F adoptions (and also NT in M cropping system) were within the confidence interval of the breakpoint the regression models. The subsequent positive trend in terms of environmental impact resulted in ELR values higher than 1, a threshold that represented an equal emergy contribution from renewable and non-renewable sources (Fig. 7). Finally, the sustainability ESI indicator showed exhibited a similar bilinear pattern of both EYR and ELR with the highest values by the middle of the time series (Fig. 8).

4. Discussion

Cropping systems from Pampa Region (Argentina) were evaluated using emergy synthesis in order to assess both the emergy flows that support crop production and the influence of the recent technological changes. These ecosystems have undergone significant changes since mid-1990 and the crop production models has expanded rapidly in the country, with a moderate to high use of inputs and improved agronomic practices that caused a remarkable increase of crop productivity (Viglizzo et al., 2011). Among the cropping systems analyzed in this paper, only the W/S double cropping showed a significant link in crop productivity with the new management practices (in this case, the herbicide-resistant cultivars). Beyond the specific effect of the adoption of a technology that increases the yield by improving weed control, it is likely that this change in trend is associated with breeding programs that were implemented due to the explosive adoption of technology for herbicide resistance in soybeans (Dill et al., 2008). Additionally, the wide adoption of a technology is also associated with an improvement in agronomic management techniques such as planting date or the time of fertilization that are also likely to influence the final crop yield. Beyond the shift in W/S double cropping, the three systems

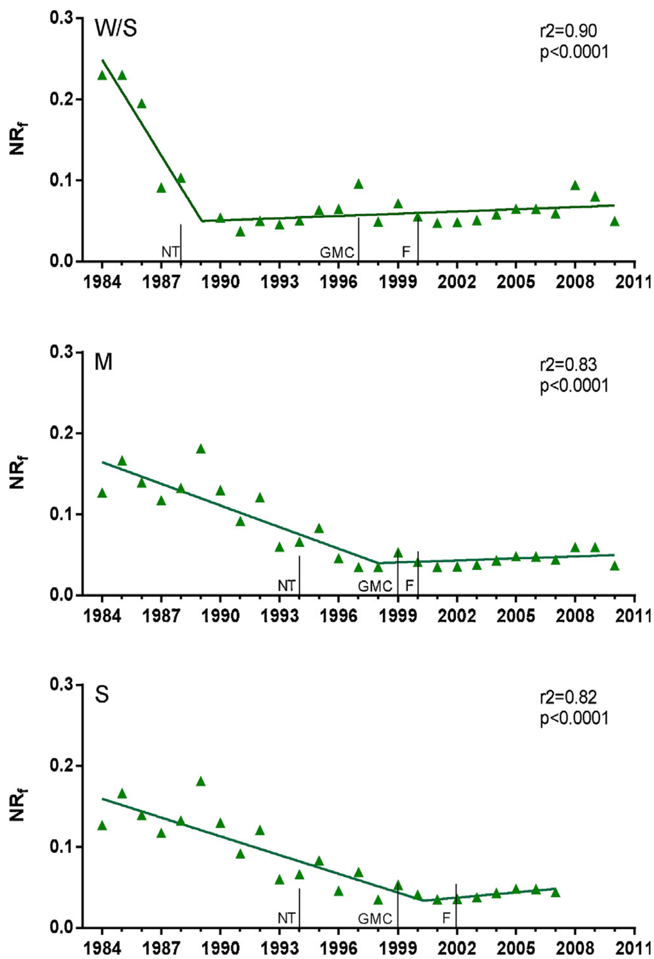


Fig. 4. Long-term changes of free local non-renewable resource fraction (NR_f) from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied. Vectors in year axis indicate the adoption of no-tillage (NT), genetically modified organisms (GMC) and fertilization (*F*).

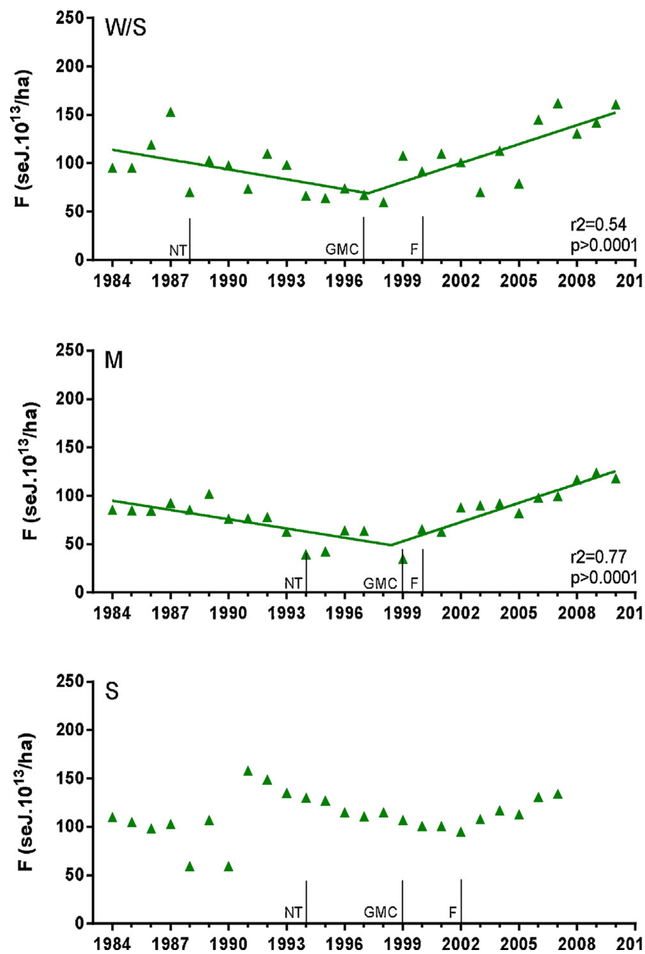


Fig. 5. Long-term changes of purchased services and materials (*F* in Fig. 1) from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied.

analyzed showed a tendency to increase yields with either a more erratic behavior (spring soybean) or as a continuation of an increasing trend prior to the adoption of new technologies (maize).

A comprehensive analyze of a cropping system should include a measure of the farmer benefit (crop productivity) and the environmental benefit (the use of renewable resources). The performance of the cropping systems studied showed that the metabolism of these systems is very close to achieve high local productivity combined with an acceptable environmental performance. One of the symptoms of a desirable functioning is the noticeable reduction in consumption of non-renewable emergy that comes from nature, denoted by the NR_f indicator. In agricultural systems, this flow is mainly represented by the services provided by the soil (i.e. fertility, water availability). This reduction was clearly related to the adoption of a no-till system which prevents soil erosion soil processes. In environmental monitoring and assessment programs, it is possible to find estimates of the costs involved in these erosion processes by means of the market costs of replacing services provided by soils after degradation with fertilizers, or some equate downstream remediation costs. However, the assessment of the soil erosion cost in emergy terms represented an enhanced accounting framework because the allocation of value is based donor (Pulselli et al., 2011; Turcato et al., 2014; Vassallo et al., 2013). According to this framework, the value is embodied in natural capital (e.g. topsoil) predicated on the environmental work required to produce it rather than on services that stock provides (Cohen et al., 2006). This 'donor-side' perspective, in which all systems and processes are invariably looked at from the point of view of the larger natural system that encompasses and supports them through a complex web of energy and material flows, should be always coupled with the utilitarian user-side or 'usefulness' perspective, in which the value only stems from utilization by humans (Ulgiati et al., 2011b).

The cropping systems exhibited not only an increase in crop productivity but also a negative trend in transformity, indicating higher values of efficiency in emergy use for crop production. A particular pattern of this trend correspond to maize cropping system, which seems to have reached a lower limit to the value of transformity, despite the observed increases in yields and input use (Fig. 5). For any energy transformation, there is an optimum loading, and thus optimum efficiency that produces maximum power (Odum and Pinkerton, 1955). The transformity that accompanies the optimum efficiency for maximum power transfer has a theoretical lower limit that systems may approach after a long period of self-organization. Transformity results would indicate that the maize cropping system has reached the most efficient structure for emergy transformation after both environmental and economic competition for a long time (Odum, 1996).

In a context of a measured increase on crop productivity and an increase (or stabilization at higher values in the case of maize) on the emergy efficiency, the analysis of emergy indicators can give us more reliable clues about cropping system sustainability. A sustainability assessment can be made by using the absolute indicator values, or its temporal trajectory, as a proxy for forecasting the

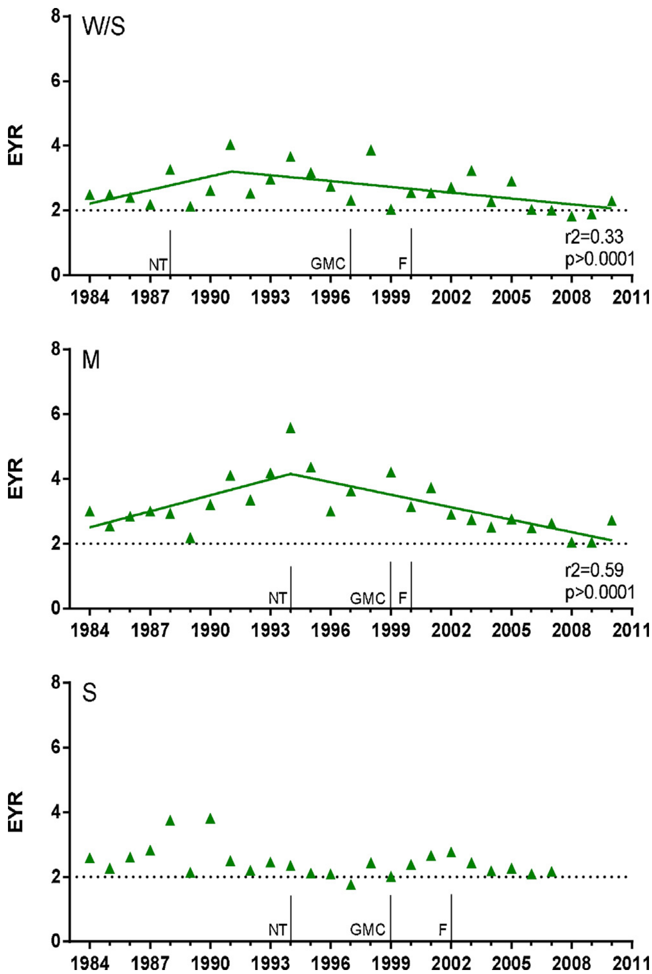


Fig. 6. Long-term changes of the emergy yield ratio (EYR) from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied. Vectors in year axis indicate the adoption of no-tillage (NT), genetically modified organisms (GMC) and fertilization (*F*). The dotted line shows EYR = 2, the state of equal emergy contribution from economy and nature (see text for calculation details).

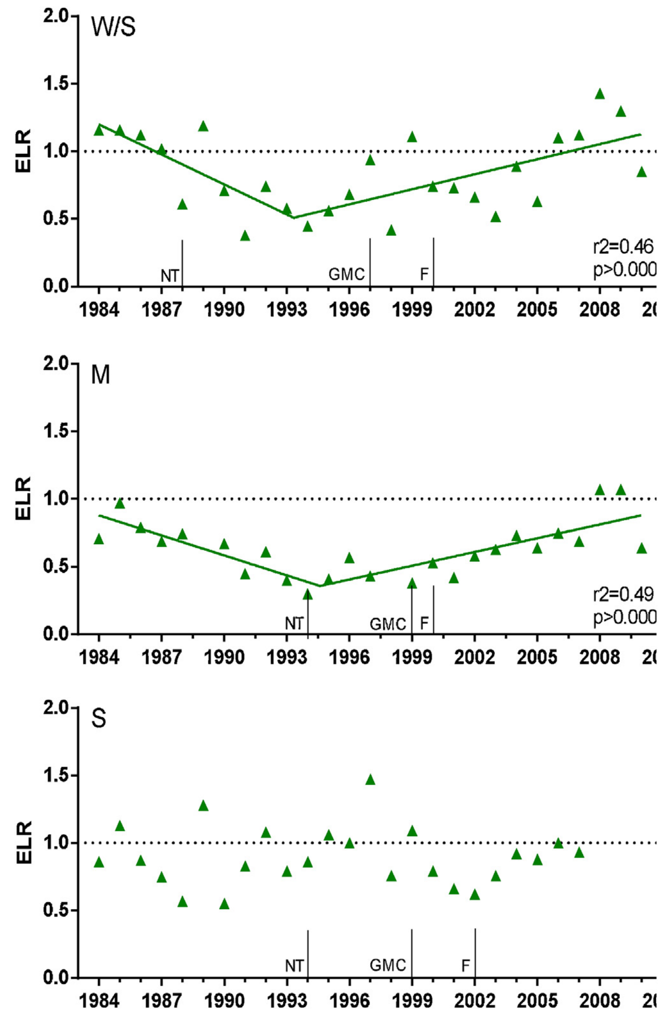


Fig. 7. Long-term changes of the environmental load ratio (ELR) from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied. Vectors in year axis indicate the adoption of no-tillage (NT), genetically modified organisms (GMC) and fertilization (*F*). The dotted line shows ELR = 1, the state of equal emergy contribution from renewable and non-renewable sources (see text for calculation details).

future system state (Tilman et al., 2011). When the absolute values of the indicators in the entire time series are analyzed, it is possible to find a common pattern for the three systems studied. First, the EYR ratio, that is a measure of the ability of a process to exploit and make available local resources by investing outside resources (Cavalett et al., 2006) was always higher than 2 (despite not display a definite trend for spring soybean). These values are higher than other similar cropping systems such as soybean in Brazil (ranged 1.18–1.78) (Ortega et al., 2002), soybean systems of Italy (ranged 1.98–2.32) (Panzieri et al., 2000) and maize production systems of Italy (ranged 1.19–1.53) (Ulgiati et al., 1994). A value of EYR = 2 reflects the state of equal emergy contribution from economy and nature. These results indicate a pattern of sustainable management, as evidenced in the observed ability of cropping systems to capture an equivalent amount of energy of the nature regarding inverted from the economy. This return is based not only on excellent agroecological conditions of the study area for crop production but also agronomic decisions associated with the use of inputs (i.e. use of pesticides or fertilizers) or crop management (i.e. planting dates, of crops, time of application of external inputs). The range of ELR in time series studied (0.30–1.43, for all the cropping systems) is substantially lower than in other cropping systems studied such as corn (ranged 2.49–5.63) and wheat (3.4) production systems of Italy (Ulgiati et al., 1994), lupine/wheat rotation (5.5) in Australia (Lefroy and Rydberg, 2003), banana cropping systems in French Wes India (ranged 7.83–11.11) (de Barros et al., 2009) and the overall value for Chinese agriculture in year 2000 (2.72) (Chen et al., 2006). Regarding the range of the ELR observed values for the time series studied, the cropping systems frequently exhibited values lower than 1.0. These values are substantially lower than those reported in other cropping systems such as the ELR = 5.5 for the lupine/wheat rotation in Australia (Lefroy and Rydberg, 2003), 1.5–3.75 for cropping-grazing systems in China (Zhang et al., 2007), values higher than 7.8 for banana cropping (de Barros et al., 2009), and 3.47 and 5.68 for wheat and maize in China biofuel cropping systems (Dong et al., 2008). Clearly, these results placed the cropping system studied in a situation of relatively low dependency from outside and low degree of support from outside. Moreover, such performance is confirmed by the relatively high values of ESI, an aggregated measure of reliance on local resources and environmental loading.

Despite the relatively good performance of the studied system that can be inferred from the ranges observed in ELR, EYR and ESI in the time series studied, the trends of these indicators would represent an environmental risk. This scenario of environmental risk is particularly clear in the increasing trend in the use of external

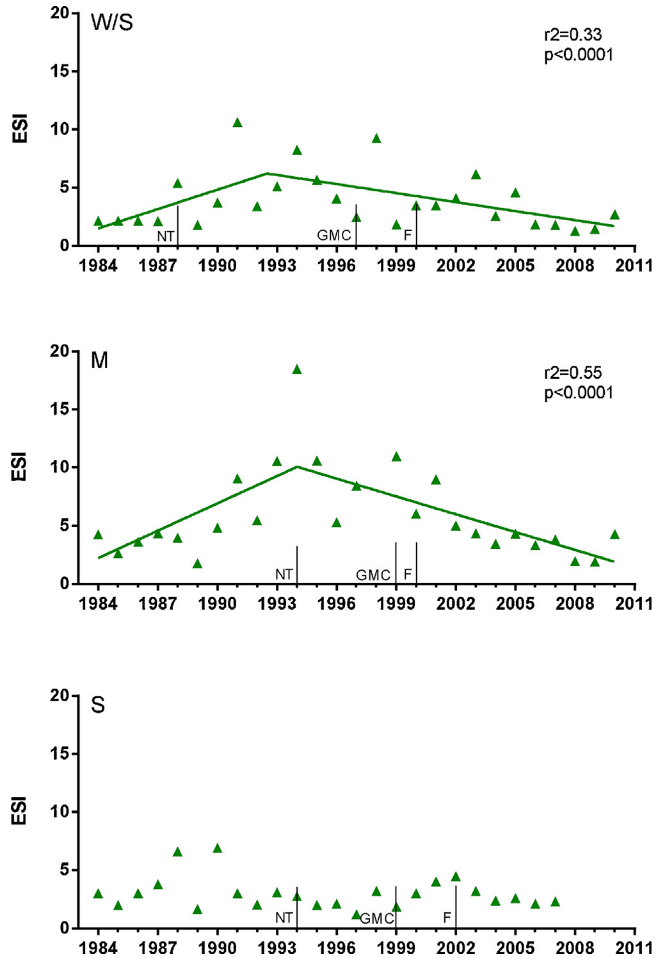


Fig. 8. Long-term changes of the Emergy Sustainability Index (ESI) from wheat/soybean double cropping (W/S), maize (M), and spring soybean (S) cropping systems during the time series studied. Vectors in year axis indicate the adoption of no-tillage (NT), genetically modified organisms (GMC) and fertilization (*F*).

emergy, which was strongly linked to the adoption of new technologies. This link between new technologies and high dependence on external inputs, would explain the common trend among energy indicators with initial improvement and a breakpoint at the time of the adoption of new technological production models. In this sense the downward trend toward the end of the series studied is consistent with what happened in other agricultural systems where a shift toward more intensive production took place (Chen et al., 2006), and reinforces the idea about the decline of net-energy yields (often measured as the food energy produced to the commercial energy invested) of modern agricultural systems relative to earlier, pre-industrial or less intensive systems (Rydberg and Haden, 2006).

5. Conclusion

In this paper, the use of emergy synthesis was applied to the study of three cropping systems with the aim of detecting changes over their long-term performance. Such a long-term study is relatively scarce in emergy analysis of cropping systems. The findings indicated that cropping systems tended to increase their productivity and that this trend has been accompanied by an increase in the efficiency of emergy consumed. Ranges of the emergy indicators would place the extensive crop production systems of the Pampa Region among the best both in the return of the inverted emergy and in the environmental impact. However, the negative trend of these same indicators after the adoption of new production technologies would pose a precautionary scenario with reference to long-term sustainability. The lower level of inputs used cropping systems of the Pampas region with respect to those of the more developed economies, suggests that a possible increase in the use of inputs to boost crop yields is likely to accentuate the negative trend detected. The changes detected in the historical analysis largely replicated what happened at the regional level in terms of technology adoption. Therefore, although the results are of particular agricultural ecosystem, they allow you to extend the findings to other ecosystems in the Pampas region with similar characteristics.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2014.06.016.

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