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The use of EPIC model to study the agroecological change during 93 years of farming transformation in the Argentine pampas

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Abstract

A non-conventional use of the EPIC simulation model is proposed to analyse and interpret changes in agroecological functions during a 93-year farming period in the Argentine pampas. The simulation was divided in seven different time periods in order to process data representing significant combinations of weather (rainfall and winds), land use (land allocated to crops and pastures), and technology (agronomic practices and farming inputs) conditions. EPIC parameters were modified according to those conditions for calibration. Model validation involved the replication of relevant past ecological and agricultural events recorded in historical documents, or quantified in regional statistics, field measurements, and experimental data sets. EPIC seems to be useful tool for (1) making sound ecological interpretation and inference, and (2) testing applications of ecological principles in farming. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: EPIC model; Farming history; Agroecological processes; Argentine pampas

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1. Introduction

The historical interpretation of functional changes in agroecosystems is useful to enrich the theoretical knowledge on agriculture and ecology, and to support well-founded decisions in applied fields such as soil-, farm- and land-management. Nowadays, trends in ecology studies combine and complement different approaches,

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methods and information sources to strength the interpretation of ecological processes (Carpenter et al., 1995; Foster et al., 1998; Fuller et al., 1998; Butterbury and Bebbington, 1999; Debussche et al., 1999). This criteria is particularly important to integrate large ecological pictures when basic information is fragmented or unavailable.

In this paper we explore the use of well-developed simulation models as an analytical tool to complement ecological studies. A non-conventional use of the EPIC simulation model (Williams et al., 1984) is proposed to analyse and interpret changes in agroecological functions during approximately one century of farming in the Argentine pampas.

A critical point in this study is the validation of the model in order to reproduce, in historical terms, a reliable representation of events. We focused on how accurately the model replicates relevant past ecological and agricultural events recorded in historical documents, or quantified in fragmentary statistics, field studies, and experimental data sets. Once the validation demonstrated that the model can consistently reproduce critical ecological and agricultural facts that have taken place in past decades, further agroecological studies would be possible following this approach.

2. Materials and methods

2.1. The study area

The study area was selected taking into account the availability of basic information suitable for the model. The area is part of the so-called subhumid pampas, with approximately 1 million ha of the best arable lands of La Pampa province, which are located on the Western side of the central pampas in Argentina (Fig. 1). Cattle and crop production are the dominant farming activities. Annual and perennial forage species rotate periodically with wheat, maize, and sunflower. Historically, the region was considered limited by the 500 mm annual rainfall isohyet on the West, and the 700 mm one on the East (Hall et al., 1992). However, a later work of Viglizzo et al. (1997) showed that rainfall varies cyclically, determining long-term periods of dry and humid conditions. Viglizzo et al. (1995) have demonstrated: (1) a significant Western displacement of isohyets between 1955 and 1990 in relation to the 1921–1954 period; and (2) a relative increase of spring and summer precipitation. The organic matter and nutrient endowment of soils decrease from East to West in the whole pampas, determining that fragile soils, susceptible to wind erosion, predominate in the Western lands. Cattle and crop production activities are combined in different proportion as an adaptation to rainfall cycles. Nowadays, the pasture-crop rotational matrix consists of 3–4 years of perennial pastures followed by 3–4 years of consecutive cropping. For economic reasons, during the last decades farmers tended to prolong the cropping period at the expense of the pasture period. Cattle production activities range from steer fattening on pasture, to cow–calf operations based upon annual and perennial pastures and a declining proportion of native grasslands.

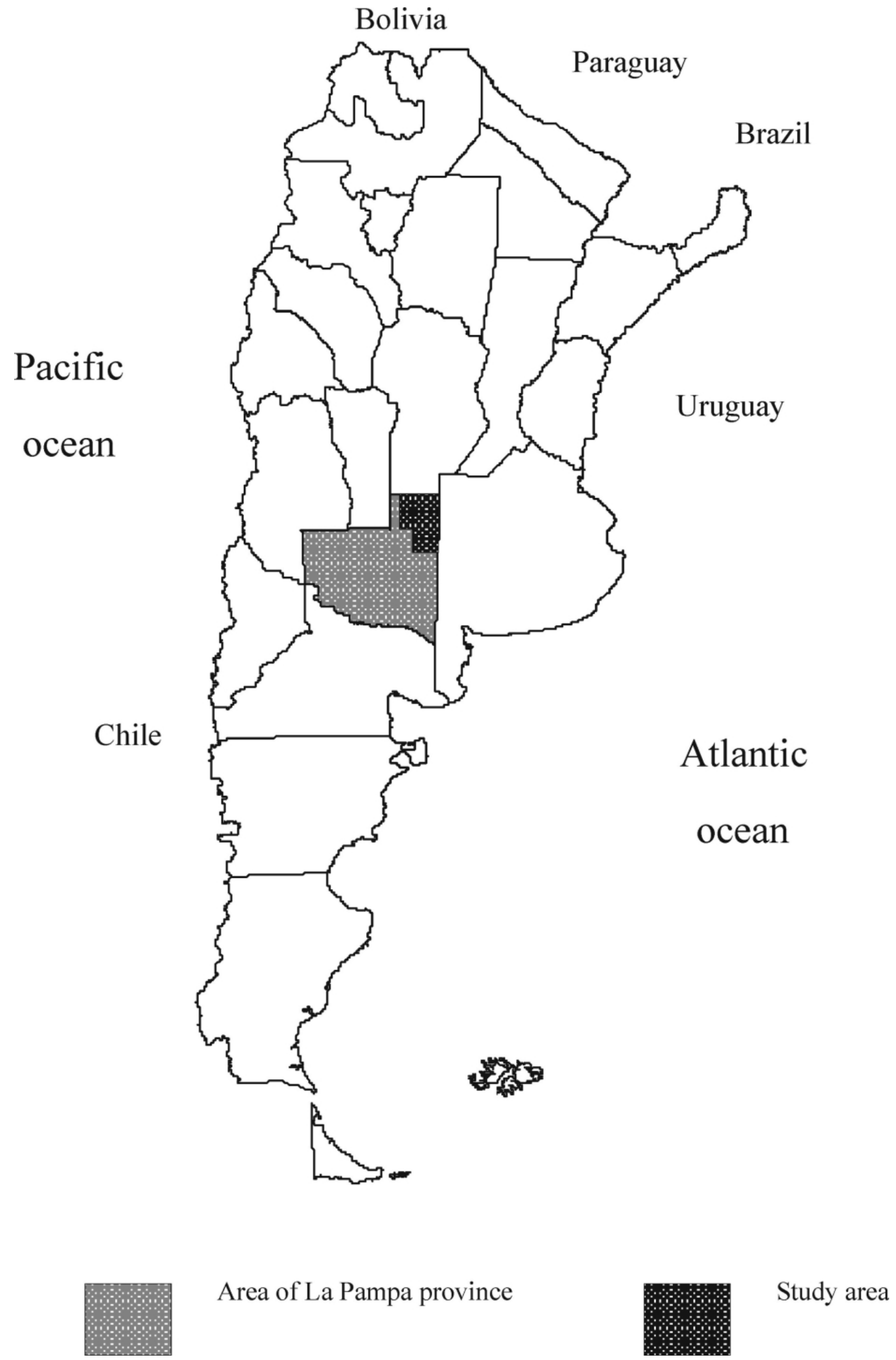

Fig. 1. Location of La Pampa province in the Argentine territory, and delimitation of the study area.

2.2. Data sources

Different sources of information have been used in this study: (1) eight general agricultural censuses of years 1881, 1914, 1937, 1947, 1960, 1969, 1973, and 1988 that comprised the totality of farms; (2) a variety of land use, production and yield statistics recorded by the Secretary of Agriculture of Argentina and public institutions of La Pampa province; (3) historical records of climate variables such as rainfall, temperature, relative air moisture and winds (INTA/GLP/UNLP, 1980; Viglizzo et al., 1995); (4) average data on soil organic matter, nitrogen (N), and phosphorus (P) concentration from various surveys and experimental studies (Hepper et al., 1996; Buschiazzo et al., 1998; Díaz Zorita et al., 1999); and (5) historical change in farming inputs and outputs as described by different authors (Covas, 1962; Covas and Glave, 1988; Viglizzo et al., 1995, USDA, 1999) and experts. Land use was expressed in terms of the relative area (%) of winter and summer crops, perennial pastures and natural grasslands with respect to the total area devoted to farming activities. The analysis comprised dominant crops such as wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. *Moench*), and sunflower (*Helianthus annuus* L.), as well as pastures based on annual and perennial grasses, leguminous perennial pastures (alfalfa, *Medicago sativa* L.), and mixed grass-leguminous pastures. Because of the lack of long-term statistical records, beef production was estimated from predictive equations (Viglizzo, 1982) that relate changes in stocking rate to meat production per hectare.

2.3. Simulation with EPIC

The Erosion-Productivity Impact Calculator (EPIC) is a comprehensive model originally developed to determine the relationship between soil erosion and soil productivity through the USA (Williams et al., 1984). The model continuously simulates erosion processes using a daily time step and readily available inputs over hundreds of years. Physical components of EPIC include hydrology, weather simulation, erosion sedimentation, nutrient flows and cycling, plant growth, plant environmental control, and tillage.

Beyond the conventional use of EPIC to predict soil erosion and productivity change, as well as a decision-support tool to determine the impact of different management strategies, we have utilised the model to specifically describe, compare and interpret functional changes of agroecosystems over a 93-year period of farming in the study area.

2.4. Data input

EPIC requires assembling a variety of databases (weather, soil, topography, management) that was collected from a flat, uniform landscape unit of 1 million ha across five Eastern political districts (Maracó, Chapaleofú, Trenel, Realicó and Quemú-Quemú) of La Pampa province. The selection of this area was determined by various reasons: agroecological homogeneity, facility to collect information, availability of statistical data, historical records of farming, experimental results, and the support of expert knowledge. The simulation was divided in seven different time periods (1907–1920, 1921–1928, 1929–1948, 1949–1960, 1961–1980, 1981–1988 and 1989–1999) in order to load data representing significant combinations of weather (rainfall and winds), land use (land allocated to crops and pastures), and technology (agronomic practices and farming inputs) conditions.

Weather data was loaded using a combination of recorded and generated weather *inputs. Data included precipitation, maximum and minimum air* temperature (°C), solar radiation (MJ/m^2), relative humidity (%) and wind speed (m/s). Daily precipitation records were initiated in the 1920s, so the corresponding inputs had to be randomly generated for the period 1907–1919. It was only in the 1940s that systematic records were collected for the rest of the weather variables. Daily data sets were randomly generated for the previous period. Annual and monthly average precipitation figures, with the seasonal distribution of rainfall, are showed in Table 1.

Table 2 summarises input data about initial soil property conditions (INTA/GLP/UNLP, 1980). Four layers are relevant in the study area from an agricultural point of view. Data included soil layer depth (m), bulk density (Mg/m^3), field capacity (m/m) sand (%), silt (%), soil pH, organic carbon (%), sum of bases (cmol(+)/kg), calcium carbonate (%), cation exchange capacity (cmol(+)/kg), coarse fragments (%), initial nitrates (g/ton), initial labile phosphorus (g/ton), phosphorus sorption ration, and organic phosphorus (%). Values of other soil variables were estimated by internal algorithms of the program. Given that landform is flat in the study area, a slope of 5 m/km was adopted for this work. Taking into account various field measurements (Puricelli, 1985), the nutrient and organic carbon endowment was increased by 55% in order to characterise the initial condition of soils in the pre-farming period.

Table 1
Average monthly and annual precipitation for each study period between 1907 and 2000

	Period						
	1907–1920[a]	1921–1929	1930–1948	1949–1960	1961–1980	1981–1990	1991–2000
January	75.8	77.5	61.2	65.5	107.2	128.8	90.1
February	86.1	86.6	61.5	79.2	93.0	113.2	120.4
March	65.3	77.0	87.5	71.2	104.4	141.6	138.4
April	73.4	64.0	45.4	45.8	64.5	79.9	90.5
May	33.4	34.4	30.7	24.1	27.7	42.1	31.6
June	16.1	19.9	15.8	26.7	23.7	15.8	17.5
July	25.6	27.1	16.2	22.0	14.7	33.9	9.3
August	25.1	23.1	17.9	13.4	23.0	19.4	28.3
September	49.9	45.5	36.1	30.8	42.9	53.2	33.9
October	79.4	82.4	69.9	78.8	81.0	86.2	80.6
November	85.2	81.4	66.1	64.6	97.3	98.1	81.7
December	86.3	87.0	76.4	63.0	96.4	100.8	181.9
Accumulated	701.6	705.9	582.9	585.1	775.8	913.0	904.2

[a] Generated by the model.

Table 2
Some relevant parameters of EPIC model regarding the initial conditions of soil properties

Soil property	Soil layer			
	1	2	3	4
Depth (m)	0.54	0.87	1.09	1.52
Bulk density (mg m^{-3})	1.19	1.32	1.53	1.78
Field capactiy (m m^{-1})	0.3	0.3	0.22	0.06
Sand (%)	63.5	68.8	69	70.4
Silt (%)	12.7	10.6	9.4	7.5
Soil pH	6.6	7.3	7.5	8.9
Organic carbon (%)	1.02	0.28	0.26	0.09

2.4.1. Data on land-use were obtained from eight national censuses that comprised 100% of the farms, and annual surveys

According to long-term changes in the land allocation pattern, various historical rotation matrixes were reconstructed involving different alternatives of land use. Given that tillage technology showed large variation in time, predominant tillage practices in different historical periods were superimposed to the historical variation of land use in Fig. 2. Based on measurements about machinery efficiency, adopted values for seeding and harvest efficiency increased significantly in successive analysed periods. Crop varieties were successively substituted in order to update their genetic potential along the study period.

2.5. Model calibration

Although the model is flexible enough to perform under a variety of environments and farming conditions, calibration was necessary before running the model for the study area. The calibration involved a modification of EPIC submodel parameters according to the predominant weather, land-use, and agronomic conditions of each analysed period.

Taking into account empirical and scientific evidence as well as historical chronicles, the model suffered successive calibrations to reproduce changes in climate, land use, crops and agronomic practices. Rainfall data was not constraint, but wind records (intensity and frequency) were available only since the 1940s. Historical evidence indicates that intensity of spring and summer winds for the 1930–1950 period were clearly above the average values of previous and later decades. Winds during such critical period were randomly estimated by taking into account the upper range of current available series. That meant an increase of 55% in wind intensity regarding average figures. Data on land use was obtained from the general censuses mentioned above. Tillage operations (Fig. 2) and weed control were modified according to historical transformations of farm machinery in different periods (USDA, 1999).

Estimation of nutrients dynamics in the model is partially driven by changes in land use, soil water content, and tillage operation. The calibration of gain, loss and

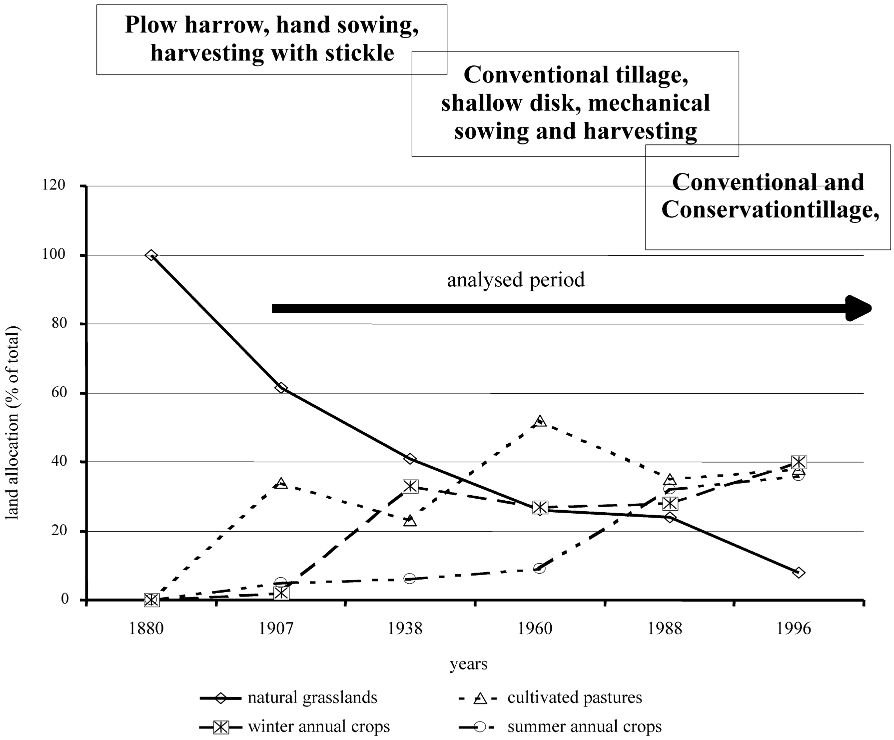

Fig. 2. Historical changes in land use and predominant tillage implements and procedures along the analysed period (1907–2000).

transfer of nutrients was in part constrained either by insufficient data, or scarce data that do not cover a varying range of soil water conditions, land use and agronomic practices. In our case, the models of N and P dynamics were adjusted through a feed-back procedure by comparing EPIC outputs with fragmentary data from experimental data and other sources of information collected during the 1980s and 1990s (Galantini et al., 1992; Panigatti, 1992; Videla et al., 1994; Brenzoni and Rivero, 1996; Casanova et al., 1996; Hepper et al., 1996; Mazzola et al., 1996; Buschiazzo et al., 1998; Dı́az Zorita et al., 1999; Dı́az Zorita, 2000; Martino, 2000).

Major components of the long-term water budget are precipitation, evapotranspiration, infiltration, percolation, recharge and discharge. Evapotranspiration was calculated as water evaporated from soils plus water transpired by plants. Infiltration is considered the difference between rainfall and runoff. Percolation is the difference between infiltration and evapotranspiration. Recharge is percolation reaching the water table (Steinheimer et al., 1998). In this work, the main components of EPIC's hydrological process, as described by Williams (1995), were precipitation, evapotranspiration, runoff, percolation, and lateral subsurface flow. Only precipitation, evapotranspiration, runoff, percolation, and lateral subsurface flow were considered pertinent to the present study. Data on precipitation came from rainfall statistics, or alternatively when statistics were not available, from internal random generation. Evapotranspiration was calculated in EPIC as a function of potential evaporation of water from soil and plants, following some of four alternative models to estimate potential evaporation. EPIC estimated runoff as a function of soil type, land management, and soil water content. A storage routing method was used to simulate percolation (downward water flow) through layers in the soil profile. Lateral subsurface flow was simulated at the same time as percolation for each soil layer. The flow partitioning between percolation and lateral subsurface movement responded to land slope and saturated conductivity. EPIC generates the hydrological variables even if the required data are not available, by internally generating the lacking or missing data from local weather statistics.

Different tillage implements and procedures were simulated to account for the impact of evolving tillage technology on soil erosion and soil properties along the study period. Specific parameters provided by the model regarding predominant utilised machinery, were applied to simulate the tillage depth and mixing efficiency of soil components and residues on the surface. Maximum tillage and plow harrow were applied since the early 1900s until the 1950s. A conventional tillage based on shallow disk began in the 1950s. A conventional conservation tillage was introduced during the 1960s, when stubble mulch and programmed fallow became popular. During the 1970s and 1980s, stubble mulch was common, and minimum tillage (mainly chisel) with herbicides were adopted. Minimum tillage was extensively utilised during the 1990s, and no-till practices coupled to increasing use of herbicides had a rapid expansion. As tillage type changed, the number of tillage operations per fallow period decreased, and the amount of crop residue remaining on the soil surface increased.

Ecological processes in livestock and crop production were analysed in separate components. Thus, hydrology, soil erosion and the dynamics of nutrient varied according to the type of system component that we have analysed. Average values for the whole system were the result of the relative allocation of land to crop or to livestock activities. As far as land allocated to crops increased with time, ecological processes tended to move away from those that are typical of pastoral production, and tended to resemble more to those that are characteristic of pure cropping systems.

2.6. Model validation

The EPIC validation process focused primarily on: (1) testing the EPIC crop yields against statistical yields; (2) determining the model's accuracy to replicate periods of high erosion according to historical chronicles; (3) comparing N flows and pools with field measurements and experimental data; and (4) evaluating the hydrological process by comparison with experimental and field measurements. The validation of those issues in historical terms was difficult due to the availability of incomplete long-term data sets. In many cases, the consistency of results was checked against information supplied by agronomic experts and historical, qualitative evidence. Results regarding validation of EPIC are presented in Section 2.

3. Results and discussion

A general comparison of EPIC outputs and experimental evidence is presented in Table 3. Both, simulated and measured information were focused only on crop production during the 1990 decade. It was assumed that the model is performing acceptably well if ranges of EPIC simulated results agree with ranges of measured data. As it can be appreciated, EPIC estimations fall within the ranges of statistical and experimental data. Additional information to validate the model is provided in the following pieces of evidence.

3.1. The hydrological process

As it happened with the ecological collapse (the above mentioned Pampean "dust bowl") between the 1930s and the 1950s in the semiarid pampas, another important historical event as reproduced by EPIC: episodes of soil water saturation at the beginning and the end of the century that were coincident with humid phases of the climate cycle. The dust bowl, as well as the flooding episodes, were the cause of deep alteration in land use and farming practices. Both events were well reproduced by EPIC simulations, and this can be considered an acceptable

Table 3
Comparison of EPIC estimations with field measurements and experimental results[a]

Analysed process	Study variable	Typical EPIC estimations	Field measurements and experimental results	
			Range of results	Source
Crop yield (kg/ha/year)	Wheat	800–1400	700–1600	National statistical records
	Maize	380–2200	380–2750	National statistical records
	Sunflower (1980–1999)	1100–2400	1150–2650	National statistical records
Hydrology (mm/ha/year)	Evapotranspitation	550–740	600–700	INTA/GLP/UNLP (1980)
	Soil water retention	40–165	162–171	Díaz Zorita et al. (1999)
	Runoff	0–95	0–100	Yates (1992)
Nitrogen (kg/ha/year)	N biological fixation	3–122	19–94	Brenzoni and Rivero (1996)
			123.8–169.6	Racca (personal communic.)
	Aerial incorporation	2.4–10.5	5.3	Panigatti (1992)
	N mineralisation	32–92	15–30	Mazzola et al. (1996)
			7.9–134	Galantini et al. (1992)
	N leaching	0–25	9–19	Casanova et al. (1996)
	Denitrification	2.3–8.8	7.4	Martino (2000)
	Amonium volatilisation	0.3–5.2	6–7	Videla et al. (1994)
Phosphorus (mg/kg)	Organic phosphorus	203–225	204–314	Hepper et al. (1996)
	Labile phosphorus	13.1–37.9	10.8–52.0	Buschiazzo et al. (1998)
			18.7–20.3	Díaz Zorita et al. (1999)
			20.5–68.5	Díaz Zorita (2000)

[a] It was assumed that the model is acceptably validated if the model outputs fall within the ranges of results of field measurements and experimental results from different sources.

validation of conditions that were extensively reported by historical chronicles and recent field evidence.

More specific validations were also required (Table 3). It is considered that runoff and percolation are less important than precipitation and potential evapotranspiration (PET) in determining the soil water content under subhumid conditions (López Gay et al., 1996). EPIC estimations of PET (between 550 and 740 mm/year) tended to agree with field assessments (between 600 and 700 mm/year), but showed a higher variability than those of INTA/GLP/UNLP (1980). On the other hand, EPIC estimations of soil water retention are in agreement with experimental results of 168, 162 and 171 g/kg for years 1991, 1992 and 1994 (Díaz Zorita et al., 1999) for the western semiarid pampas.

Provided that reliable field measurements on percolation and runoff are not available, the validation of the corresponding EPIC outcomes was rather difficult. EPIC figures on runoff, however, that oscillate between 0 and 95 mm/year, are consistent with theoretical estimations (Yates, 1997) that range between 0 and 100 mm/year for the study area.

3.2. Crops yield

Given that EPIC is not used in our case to make crop yield predictions, but to compare long-term changes in agroecological functions in different historical periods, a rigorous validation of crops yield was not strictly necessary.

Polynomic models were used to smooth and define long-term trends in the yield of the analysed crops. Results of Fig. 3 demonstrate that curves of estimated and recorded yield trends superimposed well considering the objectives of our work. Correlation coefficients were $r=0.63$, $r=0.71$ and $r=0.25$ for wheat, maize and sunflower, respectively. Because sunflower was introduced as a crop very late in the century, yield records are short, and consequently, variability is low. Although estimated yield trends are in line with statistical trends, the inter-annual variability of yield was not precisely estimated by the model. This can explain the lower correlation coefficient in the case of sunflower. However, some authors have indicated that EPIC is best suited for long-term simulation than for the simulation of yield variability between years (Williams et al., 1989; Kiniry et al., 1995; Cravero et al., 1999).

3.3. Soil erosion

Because of the fragile structure of soils, frequent droughts and intense winds, wind erosion has been of major concern in the western pampas. Long periods of droughts and strong winds (Fig. 4a), plus the accumulative effect of land misuse and non-appropriate soil management during the first decades of the 20th century, were cause of a big ecological collapse (the Pampean "dust bowl") during the 1930s, 1940s and 1950s (Covas, 1962; Covas and Glave, 1988). The extensive erosion that degraded arable lands, a rapid decay of soil productivity, successive crops failure, and a massive death of livestock caused a massive migration of people to other rural areas and

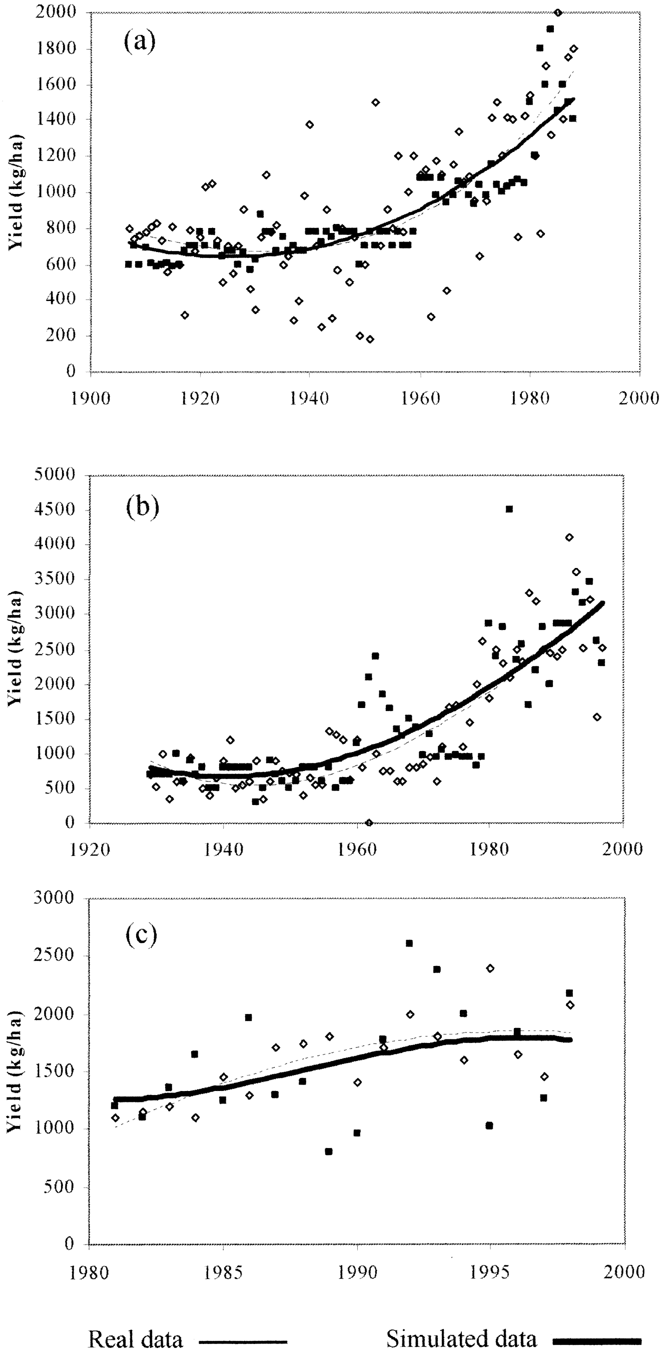

Fig. 3. Comparison of real and EPIC estimated yields of (a) wheat, (b) maize, and (c) sunflower during the study period. Note that EPIC made a better estimation of yield trends than yield variability.

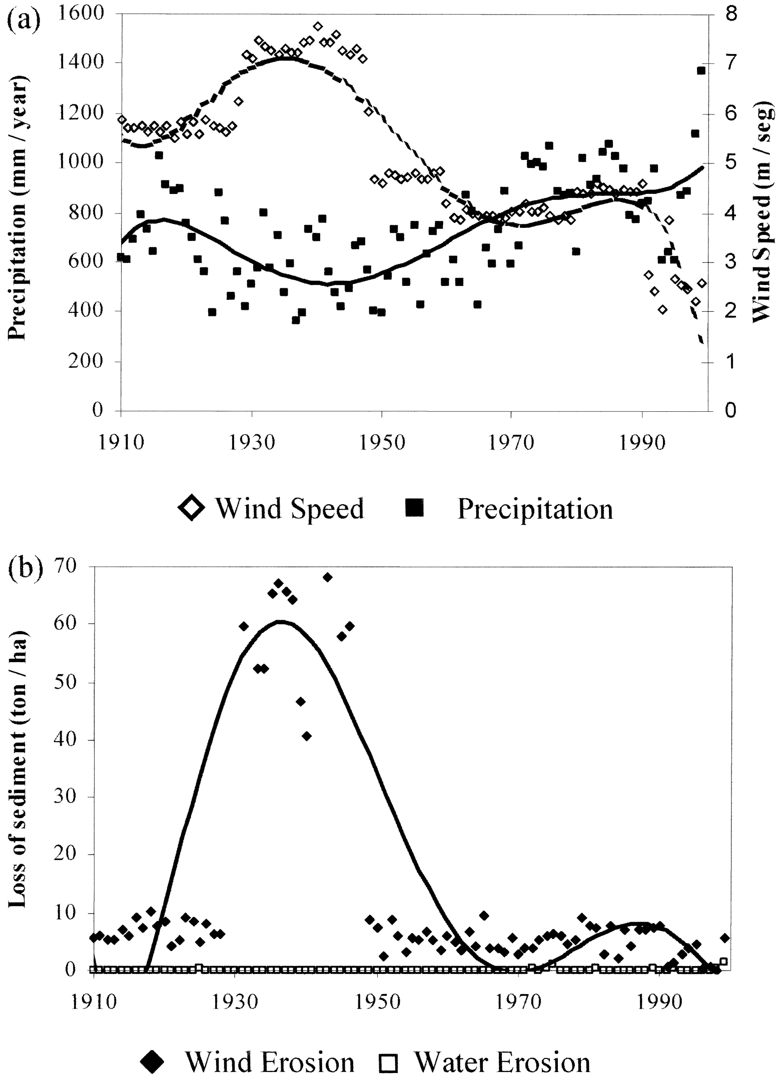

Fig. 4. Historical changes in rainfall and wind intensity (a) in the study area, and their impact on soil erosion (b) according to the estimations of EPIC.

cities. La Pampa province lost almost 50% of its population during the 1930s and 1940s due to such environmental perturbation (Covas, 1989).

EPIC estimations of soil sediments losses (ton/ha/year) by wind erosion (Fig. 4b) were consistent with the occurrence of a very dry and windy period during the 1930s, 1940s and 1950s (Fig. 4a). The amazing loss of soil sediments that happened during the Pampean "dust bowl", was clearly detected by the model. According to expert opinions, soil losses ranging between 40 and 80 ton/ha/year, and even more, were common during those dry and windy periods. Supported by FAO standards, Michelena and Irurtia (1995) considered that high erosion rates in the study region oscillate between 50 and 200 ton/ha/year. EPIC estimations of erosion rarely exceeded 10 ton/ha/year since the 1960s, which would agree with figures of 1–6 and 5–10 ton/ha/year reported by Fournier (1960), and Strakhov (1967) respectively, and 5.8–8.4 measured recently by Aimar et al. (1996) in the same region. Similar results were provided by Buschiazzo et al. (1999). The replication of those historical events by EPIC can be considered a powerful argument to support the model validation.

Given that enough field experimental results regarding the impact of different tillage systems (plow, chisel and no-tillage) on soil erosion and soil properties are available, an acceptable validation was possible. In relation to plow tillage, Alvarez et al. (1998) have demonstrated that minimum tillage doubled the amount of N mineralised in soil, and this agrees with the model estimations. On the other hand, as it was reported by Buschiazzo et al. (1998) for the semiarid–subhumid pampas, the change from conventional to conservation tillage increased the contents of organic matter, phosphorus, and soil water by 36, 23 and 14%, respectively. This observation agrees with the response of EPIC to a similar change.

3.4. The nutrient dynamics

Biological fixation was the main source of N gain to the soil system under the extensive conditions of the semiarid pampas. Fertilisation was only occasional, and almost restricted to wheat production during the 1990s. Data on N fixation were rather erratic, depending on different zones, leguminous species and varieties' and weather conditions. In the semiarid pampas, Brenzoni and Rivero (1996) reported N fixation rates that ranged between 19 and 94 kg N/ha/year. A detailed experimental research that involved two alfalfa varieties during a 4-year period (1994–1997) in different locations of the pampas (Racca, unpublished results), showed that N fixation had oscillated between 123.8 and 169.6 kg N/ha/year in the study area. During the 1980s and 1990s, and according to year climate conditions, EPIC has estimated N fixation rates that ranged between 16.4 and 155.4 kg N/ha/year (83.35 kg N/ha/year in average) for leguminous perennial pastures. Fixation rates *that* were consistently lower in previous decades might be given by technological reasons, such as the a lower capacity of leguminous species and symbiotic bacteria to fix N. On the other hand, it was estimated that approximately 5–6 kg N/ha/year are gained by direct incorporation to the soil from rainfall water (Panigatti, 1992; Alvarez, 1996).

Regarding N mineralisation, the results of EPIC ranged between 30 and 90 kg/ha/year during the period 1980–2000. These results are consistent with experiments in the semiarid pampas that reported 10–30 kg/ha/year (Mazzola et al., 1996) for natural pastures in the western areas. Figures that ranged from 14.2 to 88.4, 7.9 to 64.5, and 15.1 to 134.0 have been obtained under three different wheat-pasture rotations in the eastern part of the semiarid pampas (Galantini et al., 1992).

According to EPIC outputs, N leached was low and variable during the period 1980–2000 (between 0 and 25 kg N/ha/year). These results are in agreement with experimental measurements using lysimeters that showed losses of 19, 16 and 9 kg

N/ha/year for years 1991, 1992 and 1993, respectively (Casanova et al., 1996). Losses by denitrification are closely associated with water in soil and N fertilisation rates. EPIC estimations ranged between 2.4 and 9.5 kg N/ha/year, which agree with 9 kg N/ha/year reported by Giambiagi et al. (1990) and Martino (2000). On the other hand, the model has estimated that losses by ammonium volatilisation range between 0 and 5 kg N/ha/year, that are lower than the 6–7 kg N/ha/year reported by Alvarez (1996). However, losses of 30–40% in summer, and 5–10% in winter were reported by Videla et al. (1994).

Factors that control the P dynamics between the labile and active pools are soil water, temperature, a P sorption coefficient, and the amount of mineral in active and labile pools (Kiniry et al., 1995). Field experimental data about the dynamics of P in the soils of the study area are scarce. P fertilisation was unusual in the semiarid pampas during the study period. Given that P movements from the active mineral pool to the labile pool (available for plant use) occur at low rates, deficit of P was relatively common in the study area during the last 20 years (Buschiazzo et al., 1998). Mineralisation from the stable P pool to the labile pool was simulated by EPIC as a function of organic P weight, labile P concentration, soil water and temperature. There are only few measurements regarding the dynamics of P in soil. Hepper et al. (1996) reported that inorganic fractions of P have declined at rates of 57.3 and 138 kg/ha/year in two different soils of the semiarid pampas. Losses were attributed mainly to the crop uptake, which was estimated in 240 kg/ha for wheat production. This empirical estimation is larger than estimations made by EPIC for crops in the same region. In general, cultivated soils show a decrease of all P forms (López Camelo et al., 1996, Urioste et al., 1996), but no-tillage presents higher P values than conventional tillage (López Camelo et al., 1996).

Taken into account the inevitable difficulty to properly validate the model due to scarce data on nutrient dynamics, *a tentative comparison of N and P dynamics can be* appreciated, respectively, in Figs. 5 and 6. An average estimation of N and P balances for different periods is presented in Fig. 7. The relative importance of flows in these three last figures, is represented through arrows of varying thickness. The increasing incidence of land advocated to cultivation can be clearly appreciated by means of both, the nature of the nutrient dynamics and the nutrient balance. This type of analysis gives room to incorporate new insights to interpret the impact of long-term farming in the Argentine pampas, as well as to get practical lessons from the past to be applied in the future.

4. Conclusions

Although the lack of sufficient recorded data constrains the validation of long-term processes, in our case it was assumed that the EPIC model has acceptably reproduced some relevant historical events and ecological processes. Provided that we have used EPIC neither to predict nor to prescribe, but to make comparative analysis of different periods along the past century, rigorous validation appears not to be strictly necessary. Moreover, it should be accepted that a detailed validation of

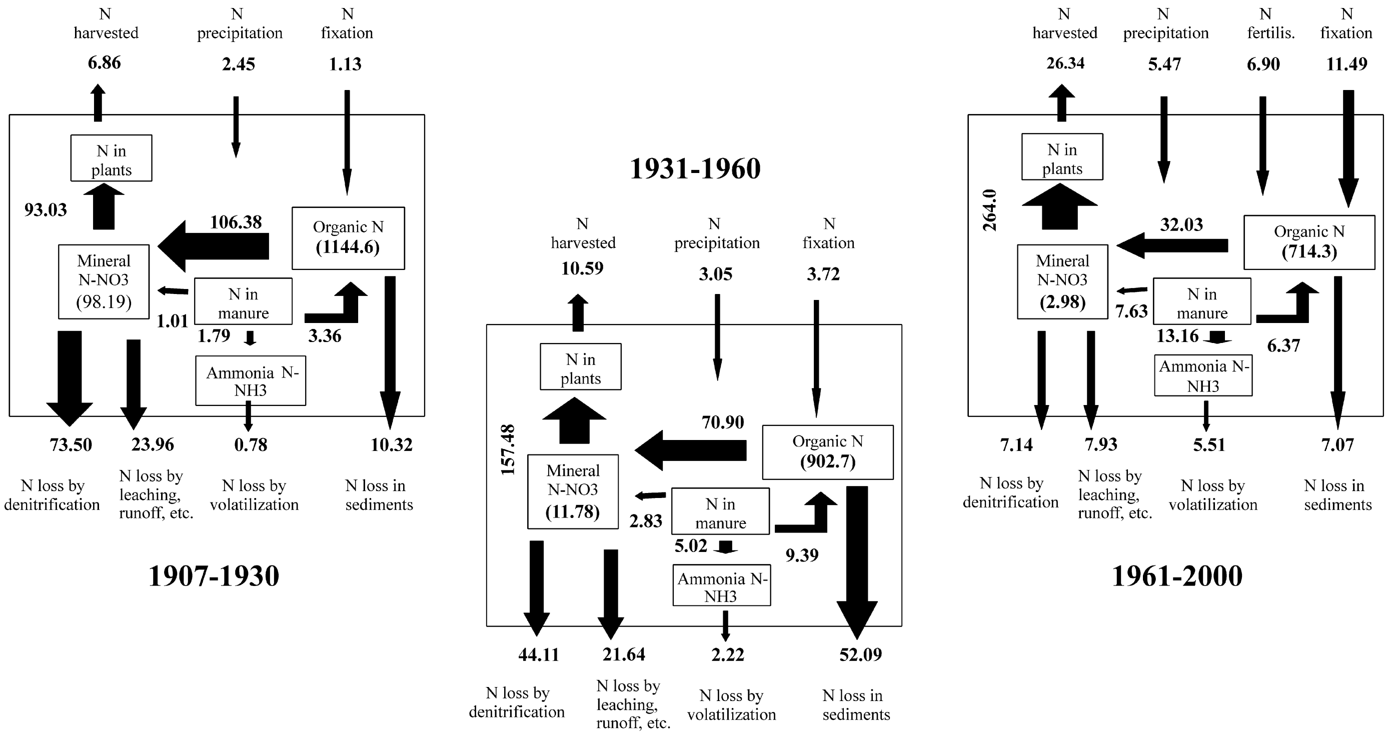

Fig. 5. Reconstruction of the nitrogen cycle in three different periods between 1907 and 2000 through the EPIC model. Highlighted figures are average values of flows (kg/ha/year) and figures between brackets in boxes represent pools (g/ton) of nitrogen for each period. Arrows of different thickness represent, approximately, the relative magnitude of inflows, outflows and internal flows.

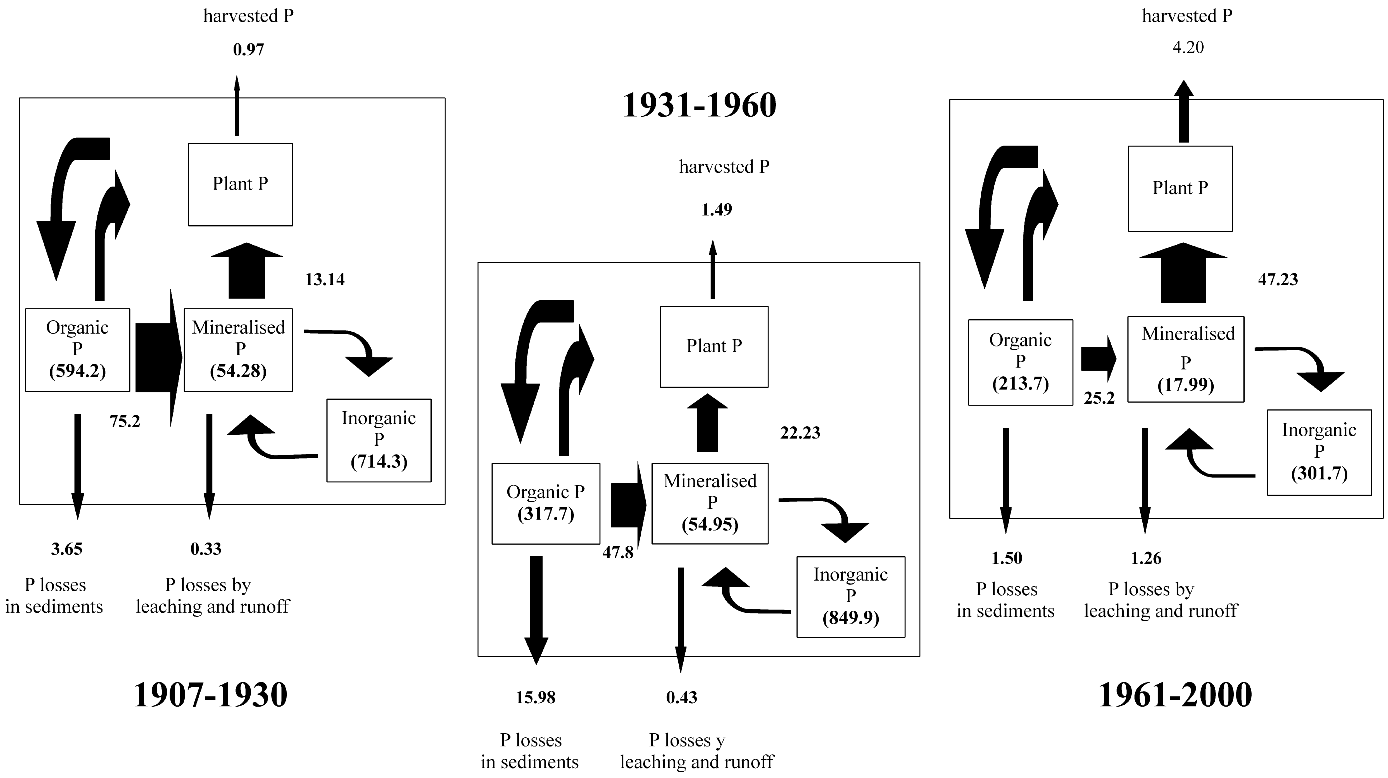

Fig. 6. Reconstruction of the phosphorus cycle in three different periods between 1907 and 2000 through the EPIC model. Highlighted figures are average values of flows (kg/ha/year) and figures between brackets in boxes represent pools (g/ton) of phosphorus for each period. Arrows of different thickness represent, approximately, the relative magnitude of inflows, outflows and internal flows.

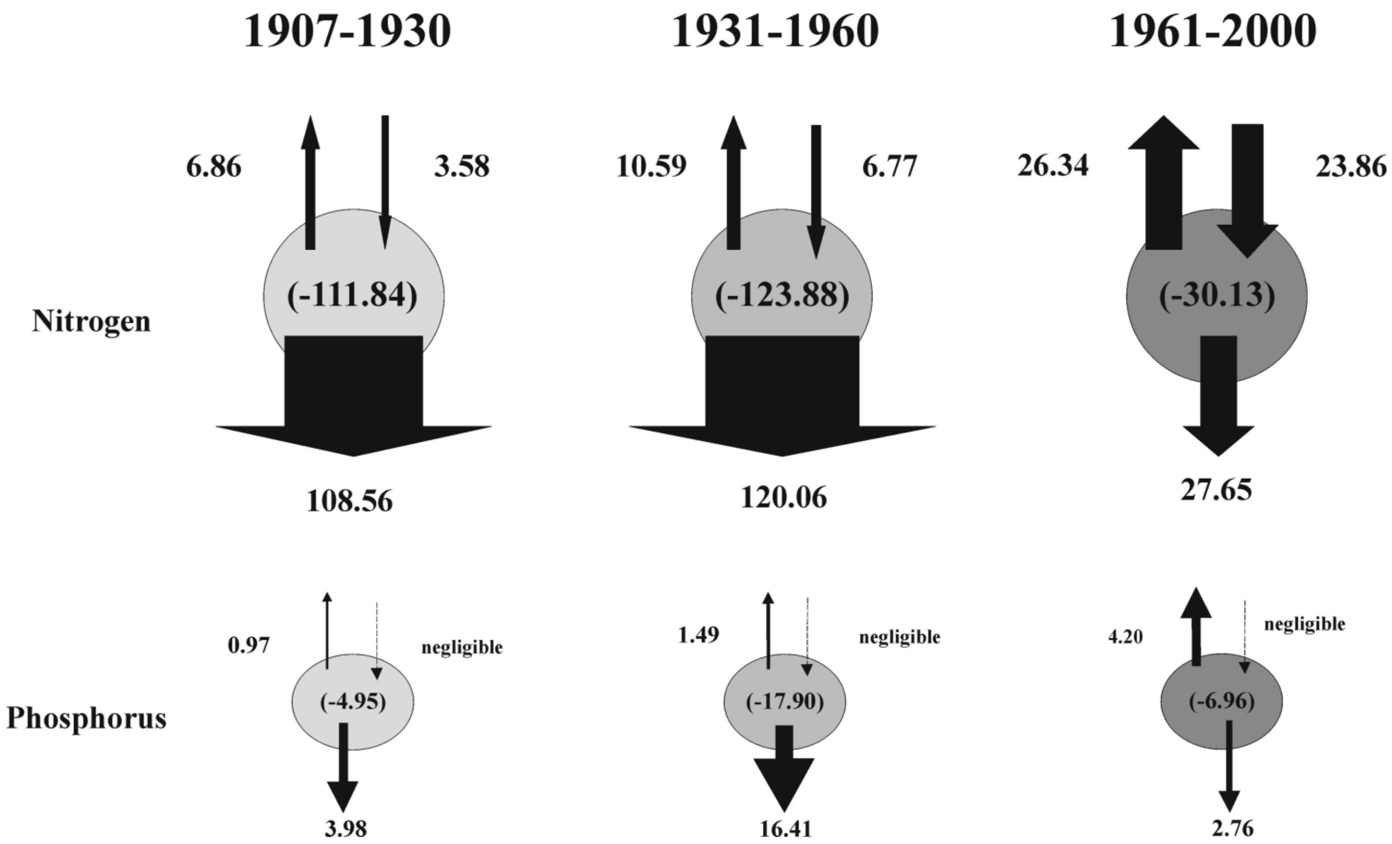

Fig. 7. Simplified scheme of nitrogen and phosphorus balances in three different periods between 1907 and 2000 . Arrows of different thickness represent, approximately, the relative importance of gains (inflows) and losses (outflows). The thickness of arrows are not comparable between nitrogen and phosphorus. Numbers between brackets represent an estimation of balances for each analysed period. All figures are expressed in terms of kg/ha/year.

ecological processes in such a long period would almost be impossible because systematic data recording began only in the second part of the 20th century.

The used validation procedure seems to be appropriate to address the purpose of our research. In historical terms, large scale ecological disturbances such as the dust bowl of the 1930s, 1940s and 1950s, and the flooding episodes at the beginning (1910s and 1920s) and the end (1970s, 1980s and 1990s) of the century, were satisfactorily captured by the model. On the other hand, an acceptable validation was possible in recent times by comparing some EPIC outputs with data sources like statistical records, field measurements, and experiments. Large differences of soil erosion, nutrient dynamics and hydrological processes in different historical periods were reflected in the model outputs. Besides, EPIC was able to make a realistic replication of the ecological impact produced by changes in tillage systems and agronomic practices.

We consider that EPIC can be used as a reliable tool to make sound ecological interpretation and inference. It seems to be a powerful tool to "open the black boxes" of ecological processes in different historical stages. The model may help to introduce new insights to the application of ecological principles in farming.

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