



A regional audit of nitrogen fluxes in pampean agroecosystems



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ABSTRACT

Calculations of nitrogen (N) budgets can help in the understanding of agroecosystem functioning and in proposing more sustainable management strategies. Changes in the main N fluxes of the pampean agroecosystems of Argentina were calculated over time. The impact of management changes on regional N budget and possible future trends were estimated. Changes in land use were quantified using national censuses data. Biological N fixation of leguminous forages was assessed using a regression model and local field experimental data. Nitrogen fixation by soybean, the most extensive grain crop, was calculated using an existing model. Fertilizer input was based upon farmer surveys, and atmospheric N input estimated using local data. Nitrogen output by grain harvest was estimated using national yield statistics and averaged grain N concentration derived from many field experiments widespread over the region. During the last 50 years cropped area has doubled as a result of the widespread adoption of soybean as the main component of rotations. The agricultural expansion included areas previously used for grazing on seeded pastures and seasonal graminaceous forages. The historical N budget of the entire region was positive but has dropped from 2.0 Mt y^{-1} in 1960 to 1.3 Mt y^{-1} at present. This reduction implies that N fixation by soybean and fertilizer application were lower than the previous livestock/pasture systems N input. During the cropping phase of rotations the N budget was usually negative in the past. Currently, in low yielding areas of semiarid environments, the N budget turned positive; meanwhile in humid climates with high productivity scenarios it remained negative. Fertilizer rates applied balanced N output in the former case but not in the latter. Partial factor productivity of N inputs increased from 3- to 6-fold during the last 50 years in the Pampas. Uncertainties related to the estimations performed are discussed.

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1. Introduction

The nitrogen (N) budget methodology is a suitable tool for understanding N cycling at global, regional (Galloway et al., 2004) and ecosystem (Spiertz, 2010) scales. Future trends of N fluxes can be predicted (Howarth et al., 2002), their possible impact on the environment can be assessed (Eickhout et al., 2006), and management options can be pointed out to increase N use efficiency (Spiertz, 2010). A global analysis showed that anthropogenic activities nearly doubled total reactive N input during the last century, mainly because of fossil fuel combustion and fertilizer application, and to a lesser extent due to N fixation by cultivated plants (Galloway et al., 2004). This increased N input to the system also lead to higher atmospheric emissions of NO_x and NH_3 and riverine fluxes (Galloway et al., 2004), which have environmental consequences. Regional soil N budgets indicated that agroecosystems were losing N in all continents during 1996 at an average rate of -12 kg N ha^{-1} (Sheldrick et al., 2002), but large areas like India

showed a slightly positive budget ($+2 \text{ kg N ha}^{-1}$), as reported for the 2000–2001 period (Pathak et al., 2010).

Different types of budgets may be calculated taking into account more or less entries to the model. The soil N budget is estimated by including inputs and outputs that cover N in harvested grain, gaseous losses and leaching (Oenema et al., 2003). A simplified version is called surface N budget in which only inputs and outputs of N are computed and losses ignored (OECD, 2001). This latter methodology, oriented to agricultural policies, can estimate N surplus, which should be avoided in order to improve N use efficiency as this surplus can be retained in the soil, emitted to the atmosphere or leached to deeper soil layers (OECD, 2001; Panten et al., 2009). Nitrogen losses are very difficult to estimate and have large uncertainties. Not accounting for these losses when calculating a nitrogen budget decreases the model uncertainty (Oenema et al., 2003). At global scale for the year 1996, surface N budget of arable land was positive ($+38 \text{ kg N ha}^{-1}$). This implies a difference of ca. 50 kg N ha^{-1} when compared to the soil N budget (Sheldrick et al., 2002). The difference corresponds to N losses. Nitrogen budgets analyzed through a fixed time period, known as audits (Sheldrick et al., 2002), have been performed at national scales and great differences were reported between regions and production systems.

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For example, audits for China showed that agroecosystem surface N budgets turned from negative (ca. -30 kg N ha^{-1}) to near neutral during the 1961–1997 period (Sheldrick et al., 2003). Nitrogen audit under German conditions showed a N surplus variation from 120 kg N ha^{-1} in 1992 to ca. 90 kg N ha^{-1} in 2006 (Panten et al., 2009).

Nitrogen partial factor productivity (ratio between product generated and N supplied) is a good indicator on N use efficiency of agroecosystems (Cassman et al., 1998). Usually, only fertilizer N is taken into account for estimating N supply (Cassman et al., 1998), but other sources should also be integrated. The combination of N audits, accounting for N inputs to or outputs from, and the partial factor productivity calculation, should indicate if N use efficiency is increasing or decreasing in an agroecosystem over time.

The Argentine Pampas covers an area of ca. 60 Mha and because of its size and yield potential is considered as one of the most suitable areas for grain crop production in the World (Satorre and Slafer, 1999). Since 1970, agriculture expanded and soybean was widely adopted as the main component of rotations (Viglizzo et al., 2001). Regional N budget have been estimated before with contrasting results depending on the portion of the Pampas considered and the evaluated period. Generally, N budget tended to start at positive values and end up with negative ones during the period 1940 to 1980 as agriculture expanded and yields increased (Viglizzo et al., 2001). Conversely, for the whole Argentinean country, including the Pampas and some other extensive areas, a positive N balance has been estimated from 1960 to 2005 (Viglizzo et al., 2011). These previous studies used non-locally developed methodologies for N fixation and exportation calculation from agroecosystems. In these estimations general averages extracted from literature were used, which could introduce serious bias in final results. In addition, some potentially important N fluxes were not considered in the models. Our objectives were (1) to estimate the soil surface N balance of the Pampas using locally-developed methodologies for N fixation estimation, local data of rainfall input and of fertilizer rate applied and N concentration in harvested products and (2) to determine the partial factor productivity of grain production in Argentina and the Pampean Region and to compare it with values obtained in other developed and developing countries.

2. Materials and methods

2.1. Study area

The Argentine Pampas is a vast plain located between 28°S and 40°S and 68°W and 57°W . The relief is flat or slightly rolling with Mollisols, formed on loess-like materials, as predominant soils (Alvarez and Lavado, 1998). Its natural vegetation consists of grasslands in which graminaceous species predominate, but forests are present in some minor areas. Forests account for about 7% of the pampean area, with planted trees introduced ca. 150 years ago, usually employed as wind barriers and occupying 0.2% of the surface (INDEC, 2002). Mean annual rainfall varies from 400 mm to up 1200 mm from West to East and mean temperature ranges from 14°C in the South up to 23°C in the North. In the humid and semiarid portions of the region, with annual rainfall above 500 mm, rain fed crops are cultivated on well-drained soils while areas with hydromorphic soils are devoted to pastures (Hall et al., 1992; Alvarez and Lavado, 1998). Because of the West–East climatic gradient and the eolian origin of sediments from Southwest to Northeast, soil texture and depth vary from sandy-shallow in the West to clayed-deep in the East, with illite the main clay mineral (Alvarez and Lavado, 1998). Along the western and southern ends of the region a petrocalcic horizon appears within the upper 1 m of the soil profile in many places (Teruggi, 1957). Around 60%

of the area is under agriculture at present and the main crops are soybean (*Glycine max* (L.) Merr.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.) and sunflower (*Helianthus annuus*) (MinAgri, 2013). As Pampean soils are fertile and crops were commonly rotated with livestock production, a low-external input regional agriculture developed (Viglizzo et al., 2001) and crop fertilization became a common practice only since ca. 1995 (MinAgri, 2013) but with low fertilizer rates (FAO, 2004). Historically, wheat was the most common crop, but it has been replaced by soybean in many areas. This latter crop occupies nowadays around 60% of the cultivated surface (MinAgri, 2013). The adoption of soybean in crop rotations came along with an expansion of the agricultural area attributed to increases in rainfall and technological improvements (Magrin et al., 2005; Viglizzo et al., 1997).

The study area was partitioned into six sub-regions (Fig. 1) by taking into account topographic, drainage, climate and soil characteristics at county scale (Table 1). On one hand, some sub-regions and the counties included were defined related to slope and drainage problems using soil survey information (INTA, 1980, 1981, 1983, 1984, 1989, 2003, 2010). Specifically, this resulted in sub-region five that showed the highest slopes of the Pampas and the sub-region six where drainage problems predominate. On the other hand, climate records were used for aggregating counties into the remaining four sub-regions. Thresholds used to perform spatial aggregation were annual rainfall of 800 mm and mean annual temperature of 16°C . Soil survey and climate information was processed as described in Berhongaray et al. (2013). Some counties were located at the margins of the proposed subregions and as their properties did not fall within the established thresholds, some minor exceptions were accepted in order to maintain the areal integrity of each pampean sub-region (Table 1).

2.2. Land use data

National censuses of the years 1960, 1969, 1974, 1988 and 2002 (INDEC, 1964, 1969, 1974, 1988, 2002) were used for surface estimation of the different land uses per county. For the year 2010 data from MinAgri (2013) of area devoted to grain crops, and Secanell (2009) of area assigned to forage resources were used. As in the census of year 2002 a detailed description of seeded pasture composition was presented, and that was not available for previous censuses, the partition between different pastures types corresponding to 2002 was assumed to be maintained along the whole analyzed period. Annual yield and its seeded surface per county for the main pampean crops was obtained from MinAgri (2013). Yield data was averaged into five year periods for smoothing some annual extremes related to interannual variability. Spline estimation of areas under seeded pastures was performed for intermediate years between censuses.

2.3. Nitrogen inputs

Alfalfa (*Medicago sativa*) dry matter production was estimated based on results from 500 annual estimations of aboveground net primary productivity obtained from 41 field experiments corresponding to 12 locations spread all over the study region (Agromercado, 1996, 2000; Spada, 2004, 2009, 2010; Spada et al., 2007; Dubois, 2009; Producers, 2004). Mean annual rainfall and average temperature of each location was obtained from climatic records and productivity was modeled as a function of climate. According to Bolinder et al. (2002), alfalfa root biomass was assumed to be similar to aboveground biomass. In mixed alfalfa–graminaceous pastures alfalfa biomass was assumed to represent 50% of total biomass (Mortenson et al., 2004). Aboveground nitrogen fixation of pure alfalfa stands was modeled using data from five long term field experiments located both within semiarid and

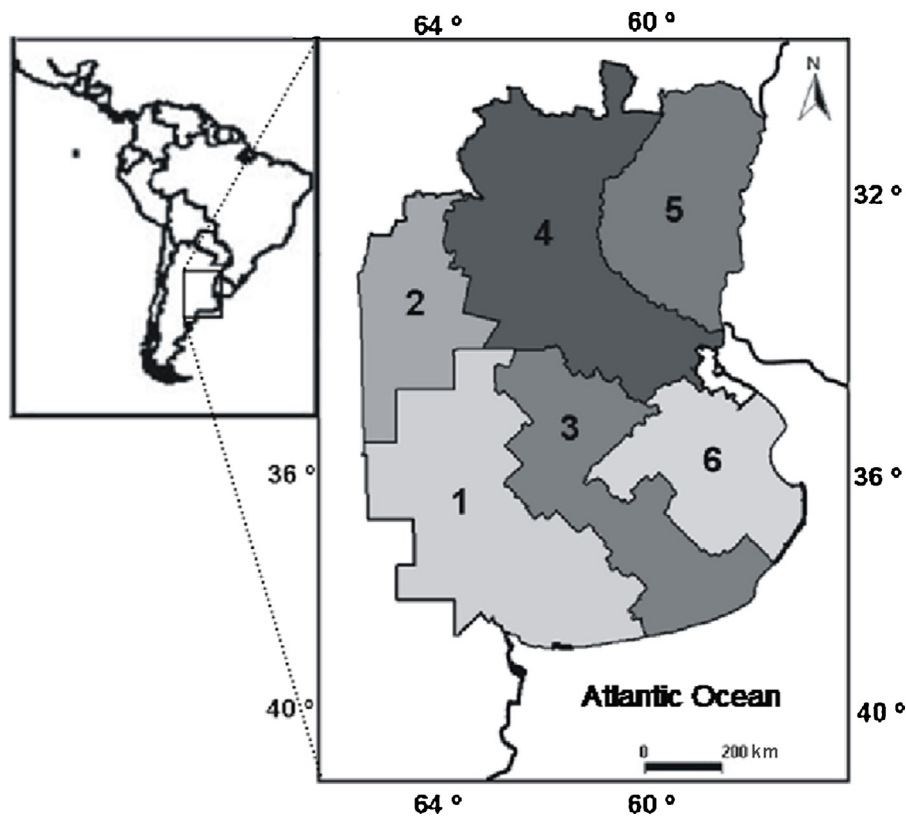


Fig. 1. Map of the Pampean Region showing the division into sub-regions performed for the analysis.

humid portions of the Pampas (Racca et al., 2001). In these experiments annual aboveground net primary productivity and N fixation were determined over a four year period. Fixation was assessed by applying the ^{15}N dilution methodology and regressed against productivity. Nitrogen input by biological fixation in seeded pastures was estimated as the sum of fixation in pure alfalfa stands, mixed stands and other leguminous mixed pastures. Aboveground fixation estimated by biomass productivity was modified by a $\times 2$ factor to account for fixed N in roots. For mixed alfalfa-graminaceous pastures estimated fixation in aboveground biomass was not corrected by root or graminaceous biomass, which were assumed to be equivalent. As alfalfa pastures accounted for 66% of total mixed pastures in the Pampas (INDEC, 2002) and there was no available model for *Trifolium* sp. fixation estimation, we assumed that productivity and N fixation by *Trifolium* sp. would be similar to those of alfalfa. In natural grasslands of the Pampas no leguminous species were normally present so N fixation in this ecosystem was taken as null (Chaneton et al., 1996).

Nitrogen fixation by soybean crops was estimated using the local model of Di Ciocco et al. (2011). This model estimates N fixation using grain yield as the predictor variable. Integration resulting from 10 field experiments performed in the Pampas, in which fixation was assessed by ^{15}N methods, defined a slope of 52 kg N ha^{-1}

for each ton DM grain ha^{-1} ($R^2 = 0.62$, $P < 0.05$). Combining this model based on soybean yield and statistical yield information at county scale (MinAgri, 2013), permitted the calculation of the overall N input by soybean crops. Nitrogen inputs by fertilization during soybean, wheat, corn, and sunflower growing cycles was estimated using site specific data of applied N rates by farmers, aggregated up to county scale for the year 2007 (RIAN, 2012). The rates estimated for this year in combination with the historical N fertilizer consumption trend were used for past fertilizer rate estimation (MinAgri, 2013). An average rate of $13 \text{ kg N ha}^{-1} \text{ y}^{-1}$ 100 cm^{-1} rainfall was used for rainfall N input estimation (Alvarez, 2001). This input was estimated by integration of six year measurements of N-nitrate and N-ammonium content of rainfall at the humid site of Rafaela (Hein et al., 1981) and relating N input to the overall rainfall of the period. Nitrogen input in rainfall was estimated at county scale and integrated up to subregion unit and regional scales using averaged rainfall scenarios for five year periods.

2.4. Nitrogen outputs

Nitrogen output from harvested grain was calculated as the product of average yield at county scale and grain N content. Average N contents of 20 kg N t^{-1} DM for wheat, 14 kg N t^{-1} DM for corn,

Table 1
Main characteristics of the Pampean sub-regions used in the analysis.

Subregion	Rainfall range (mm)	Temperature range ($^{\circ}\text{C}$)	Topography	Predominant soils	Drainage	Natural vegetation	Main land use	Surface ¹ (Mha)
1	619–786	13.8–16.0	Flat	Mollisols–Entisols	High	Grassland	Cropping–grazing	11.2
2	699–783	16.1–16.6	Flat	Mollisols–Entisols	High	Grassland	Cropping–grazing	5.49
3	770–961	13.7–16.0	Flat	Mollisols	High	Grassland	Cropping–grazing	8.31
4	814–1059	16.1–18.5	Slightly rolling	Mollisols	High	Grassland	Cropping	12.1
5	985–1156	17.5–19.1	Rolling	Mollisols–Vertisols	High	Grassland–forest	Cropping–grazing	6.63
6	878–1037	13.8–16.3	Flat	Alfisols–Mollisols	Poor	Grassland	Grazing	6.61

¹ Not taken into account cities, lakes, roads and salines.

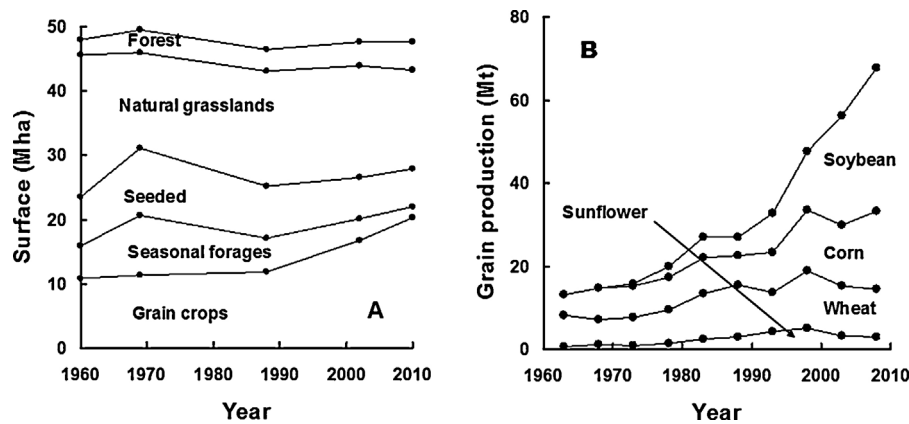


Fig. 2. (A) Evolution of surface devoted to different land uses in the Pampas. (B) Evolution of grain production for the main crops.

28 kg N t⁻¹ DM for sunflower (Alvarez et al., 2012), and 60 kg N t⁻¹ DM for soybean (Di Ciccio et al., 2011) were used. These values resulted from ca. 200 field experiments performed in the Pampas, in which grain nitrogen content was assessed. Minor crops, such as sorghum (*Sorghum graniferum*) and barley (*Hordeum vulgare*) were not taken into account because N output of these crops was less than 2% of total regional output. Around 8% of corn production is used for cow feed (calculated with data from FAOSTAT (2013) and Pastor (2004)) and a portion of grain nitrogen returned to agroecosystems but, according to the conservative criterion applied regarding the N budget, this was not computed and all grain N assumed to be an output. The overestimation produced by this simplification approximated 0.6% of total output.

Output in livestock production was estimated using data from cow population at county scale (INDEC, 1974, 1988, 2002) and fraction sacrificed annually (MinAgri, 2010; Observatorio Bovino, 2013). The average body weight (400 kg) was obtained from MinAgri (2010), assuming that 20% was rumen content and a mean nitrogen content of 3% in body tissues (Thompson et al., 1983). Nitrogen output in livestock production for intermediate time periods between censuses was estimated using splines. Milk production data was obtained from ONCA (2009). For the whole Pampean Region 4.7 Gt was estimated for 2008–2009 and no available historical data were obtained at county scale. A protein content of 3.1% (Tsenkova et al., 2000) was used for milk N output estimation. As milk N output rounded during 2008–2009 a value of less than 1% of total output, this N flux was not taken into account for N budget calculation.

2.5. Nitrogen budget and partial factor productivity calculation

Surface N budget was calculated as the difference between N inputs and outputs to and from the six sub-regions and to and from the whole pampean area for the five analyzed decades. This balance was estimated both for agroecosystems producing only annual crops and agroecosystems that combined annual crops with pastures in rotations. Partial factor productivity (PFP) of grain production and harvested grain N were calculated as the ratios grain DM:N input and grain N:N input. Partial factor productivity of fertilizer N was calculated only accounting for N input of applied fertilizer. For comparison purposes PFP of fertilizer N at country scale was calculated for some major grain production countries using data from FAOSTAT (2013).

3. Results

During the 1960–2010 period, the area occupied by forest and natural grasslands remained nearly unchanged in the Pampas (Fig. 2A). Conversely, cultivated area under annual grain crops doubled, replacing seeded pastures and annual graminaceous forage crops. This increase in grain crop area was produced mainly by the introduction and widespread adoption of soybean as main crop rotation component. Wheat, corn, and sunflower cropped area suffered minor changes during the studied time series. As yields also doubled, total grain production of the Pampas rounded a 4-fold increase (Fig. 2B).

Alfalfa aboveground net primary productivity could be estimated using climate variables as predictors (Fig. 3A). Productivity was a linear function ($P < 0.05$) of the interaction between rainfall and temperature. A model could be fitted ($P < 0.05$) for estimating biological N fixation of this forage based on aboveground productivity (Fig. 3B). The linear fit had an ordinate not different from 0 (t test, $P < 0.05$) and a slope of 19 kg N fixed t⁻¹ DM produced.

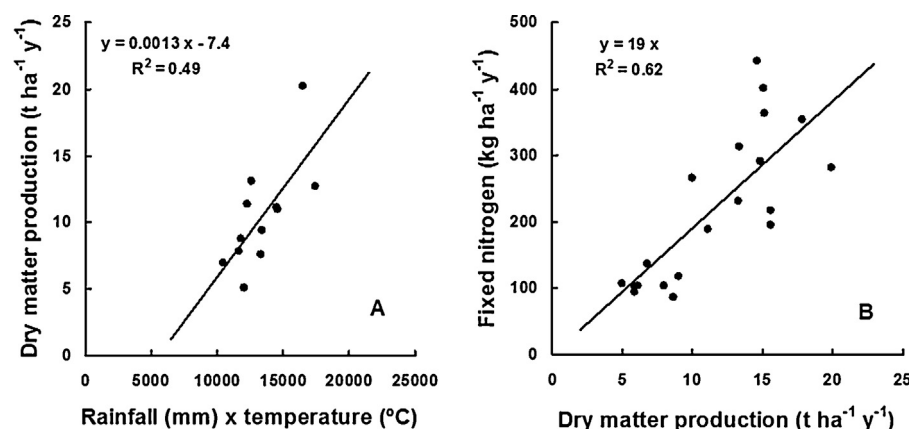


Fig. 3. (A) Aboveground dry matter production of alfalfa as a function of rainfall and temperature. (B) Fixed nitrogen in aboveground biomass of alfalfa as a function of dry matter production.

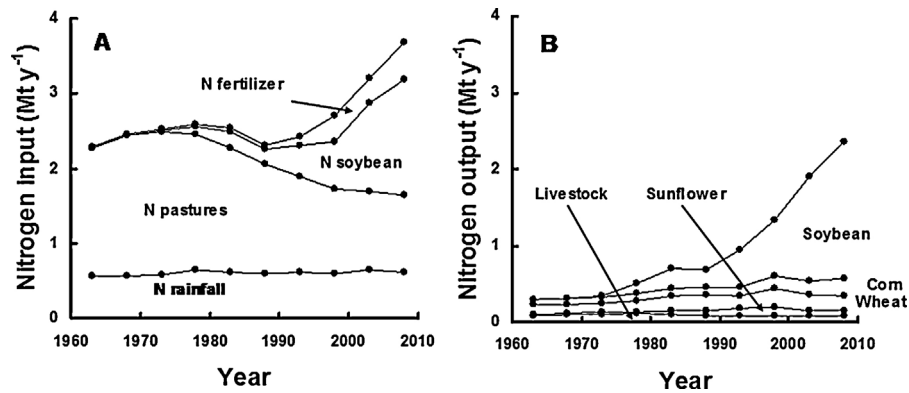


Fig. 4. (A) Evolution of nitrogen inputs to pampean agroecosystems from different sources. (B) Nitrogen output from the Pampas by grain harvest for the main crops.

Using the above mentioned tools N input to pampean agroecosystems by seeded pastures was estimated (Fig. 4A). This input decreased by 40% along the study period because of pasture area reduction. In spite of this, reduction of total N input to agroecosystems increased due to biological fixation performed by soybean crops and fertilizer use. Nitrogen input in rainfall approximated 0.6 Mt y^{-1} with minor changes over time. At present, N input to pampean agroecosystems is around the double than that of 50 years ago. Furthermore, a strong increase in outputs occurred in harvested grains (Fig. 4B), and average livestock output represented less than 10% of total output over the study period. Harvested N in grains was 11-fold greater than that of five decades ago. This increase was produced by harvested soybean grain. Around 80% of the output corresponds to this crop, which occupies nowadays ca. 60% of the cultivated area and had very high grain N content.

Nitrogen budget for the whole Pampean Region have been positive over the study period (Fig. 5). When this budget was calculated only for soils cultivated with grain crops, negative values were estimated, which recently turned to neutral. Consequently, in areas where crops were not rotated with pastures, soils lost N in the past. The historical analysis at the sub-regional scale showed some differing results (Fig. 6). Both, in the semiarid and the humid portion of the Pampas, the budgets were positive with greater gains observed under humid environments. This was because of higher pasture productivity and N input by biological fixation. As pastures were replaced by annual crops the budget tended to be less positive in recent decades. Under the pampean semiarid climate, and with a lower N output due to lower attained yields, the budget turned to positive at present. In the humid portion of the Pampas N budget remains negative under cultivation ($-7 \text{ kg N ha}^{-1} \text{ y}^{-1}$). Despite management differences between subregions, the overall budget is positive at present for all subregions and cropped areas tended to neutral or slightly negative budgets (Table 2). Grain N output is balanced in humid-high grain productive areas by soybean N fixation and fertilization meanwhile in subregions where grazing is still an important activity N fixed by pastures compensates harvested outputs.

Partial factor productivity of grain production and harvested N increased in the Pampas over time (Fig. 7). This efficiency measure increased by 3-fold for grain production and by a factor of six for grain N. Nitrogen input was much more efficiently used at present than in the past but as the partial factor productivity of N is ca. 0.60, it indicated a N surplus still existed. Harvested N partial factor productivity

had a higher increase than grain productivity because of soybean N concentration that was around 3-fold greater than in the other crops, and production increases were accounted for mainly by this crop. When only fertilizer N input was taken into account in PFP calculation, the Pampas resulted in a highly efficient N using region compared with some of the major grain producing countries of the World (Fig. 8). This also resulted from the low regional contribution of fertilizers to total N input in the Pampas. Because of the importance of the Pampas related to its contribution to the overall national Argentinean grain production, the country had an efficiency 2–4-fold higher than most of the developed and undeveloped countries worldwide.

4. Discussion

The main N input in the Pampas is atmospheric fixation. The slope of our estimation model for alfalfa falls within the boundary values of $15\text{--}25 \text{ kg N fixed t}^{-1} \text{ DM}$ in aboveground plant organs established by a meta-analysis based on numerous experiments with different leguminous species (Herridge et al., 2008) and it seemed adequate for a regional estimation. In the Pampas alfalfa and some *Trifolium* species are the most common N fixing pasture crops. Slopes of fixed N against dry matter production are usually similar between both species (Carlsson and Huss-Danell, 2003) implying that the generalization of using only one model would not impact significantly the final estimated results. Conversely, the productivity model developed for alfalfa may not be suitable to other forage species. Despite this constraint, as alfalfa based pastures are the most common seeded pastures in the Pampas and accounted for by two thirds of the total seeded surface, the possible bias in the overall estimation is expected to be small. For example, if a non-alfalfa pasture has a 20% lower productivity than that predicted by the proposed model, this would impact N fixation estimation by -7% .

When legume dry matter yield increases, expressed as a percentage of total yield, N fixation by pastures increases linearly (Carlsson and Huss-Danell, 2003). Based on data from Fig. 2 of the previous study we fitted an average slope ca. $2 \text{ kg N fixed ha}^{-1} \text{ y}^{-1}$ per 1% increase in the proportion of total biomass in legume biomass. If our assumption, that legume biomass accounted for

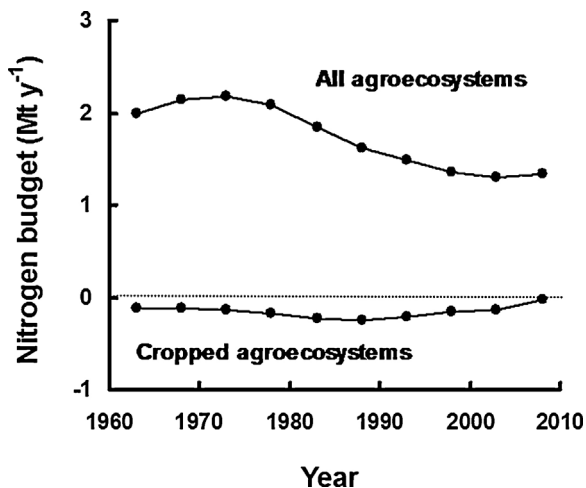


Fig. 5. Evolution of the nitrogen budget of pampean agroecosystems. All agroecosystems includes annual crop and pastures.

Table 2

Average annual nitrogen budget for each pampean subregion for the 2006–2010 period.

Subregion	All agroecosystems (Mt)			Cropped agroecosystems (Mt)		
	Input	Output	Budget	Input	Output	Budget
1	0.52	0.28	0.24	0.30	0.26	0.04
2	0.41	0.28	0.13	0.27	0.27	0.00
3	0.54	0.37	0.17	0.33	0.35	-0.02
4	1.51	1.15	0.36	1.08	1.13	-0.05
5	0.45	0.20	0.25	0.20	0.19	0.01
6	0.28	0.08	0.20	0.06	0.07	0.00
Total	3.70	2.36	1.34	2.25	2.28	-0.03

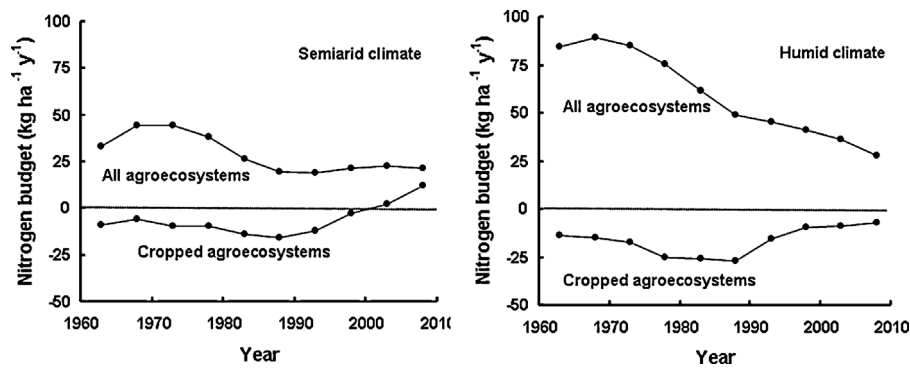


Fig. 6. Nitrogen budget of pampean agroecosystems under contrasting climate scenarios. Semiarid climate corresponds to sub-region 1 and humid climate to sub-region 4. All agroecosystems includes annual crops and pastures.

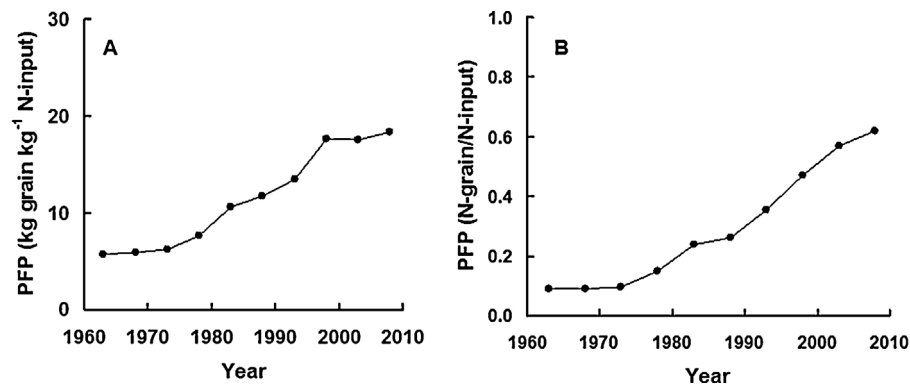


Fig. 7. (A) Partial factor productivity of nitrogen inputs (PFP) in the Pampean Region taking into account grain production. (B) Evolution of PFP taking into account nitrogen in harvest products.

an average of 50% of total mixed pastures biomass in the Pamapas is biased by $\pm 20\%$ this would be equivalent to an error of $\pm 40 \text{ kg N fixed ha}^{-1} \text{ y}^{-1}$ or a $\pm 14\%$ in our regional N input estimation. This bias would not change the sign of the estimated N budget. Some local data show that alfalfa biomass in mixed pastures ranges from 50% to 75% in the Pamapas (Romero, 2011; Romero and Ruiz, 1997). Our conservative assumption of 50% alfalfa biomass may lead to some sub-estimation of N input by atmospheric fixation.

In this case, N budget would be even more positive than the one calculated.

Nitrogen fixation by soybean, the main N input at present in the Pamapas, was estimated by a local fitted model that accounted for a lower fixation potential ($52 \text{ kg N fixed t}^{-1}$ by DM grain produced) than a more general model adjusted to results from 61 papers generated worldwide (Salvagiotti et al., 2008, $71 \text{ kg N fixed t}^{-1}$ by DM grain produced). Data of soil mineral N at sowing and

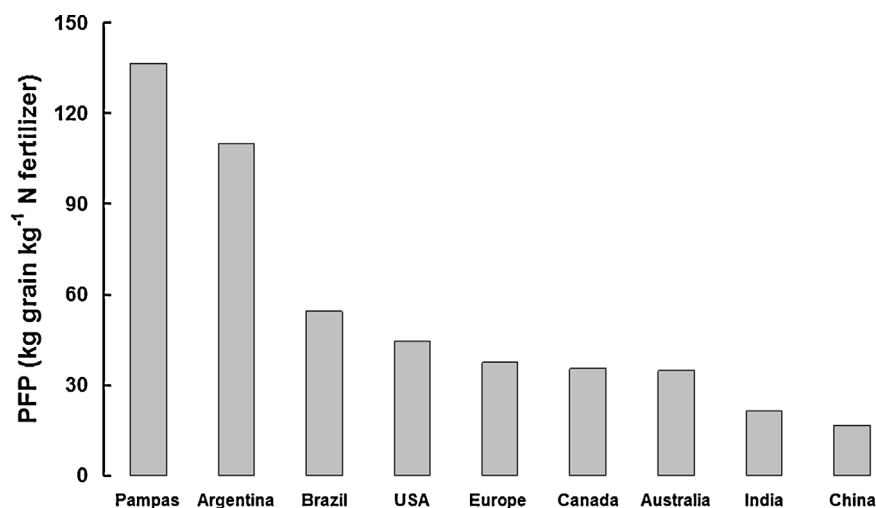


Fig. 8. Partial factor productivity of nitrogen fertilizer (PFP) in the Pampean Region, calculated using data from this study, and for some countries taking into account total cereal and oil crop production and fertilizer consumption from FAOSTAT (2013). In this latter case some oil crops were not grain crops but as their production was very small this was not taken into account as a separate item.

mineralization during soybean growing cycle are not available in the Pampas. Because soybean and corn growing cycles occupy the same time window; we assumed that N supply by the soil may be similar for both crops. Average organic N mineralization potential in the Pampas approximated 150 kg N ha^{-1} during the growing cycle of corn when soybean (Alvarez and Steinbach, 2011), corn (Sainz Rozas et al., 2004) or a fallow period (Bono and Alvarez, 2011) precedes the crop. Mineralization adds available N to the soil mineral N pool that averages ca. 90 kg N ha^{-1} when summer crops are sowing (Alvarez and Steinbach, 2011; Bono and Alvarez, 2011; Sainz Rozas et al., 2004). Adding both N sources account for an overall N availability of 240 kg N ha^{-1} . Approximately 60% of soybean in the Pampas is cultivated after soybean, 25% after corn, and 15% is produced after wheat. Only when soybean is cultivated after wheat, in a double crop in a year sequence, low initial mineral N content of the soil may be expected, because of the absence of a fallow period. Nitrogen availability is usually very high for summer crops in the Pampas. Consequently, a previous comparison of these two models showed that the worldwide model overestimates fixation in the Pampas, probably because N fixation is repressed by the naturally high soil fertility of the region (Di Ciocco et al., 2011; Salvagiotti et al., 2008), and using the local model seemed more reasonable. This methodology allowed a better estimation than a previous study in which, using available results from only two local experiments, a very negative N budget was estimated for soybean crops, with county scale average values as negative as $-100 \text{ kg N ha}^{-1} \text{ y}^{-1}$ (Austin et al., 2006). For the average pampean soybean yield of $2300 \text{ kg DM ha}^{-1}$ (2006–2010), the N budget calculated applying the local fixation model is $-8 \text{ kg N ha}^{-1} \text{ y}^{-1}$. This budget accounts for some N applied as fertilizer in phosphorus fertilizers ($5 \text{ kg N ha}^{-1} \text{ y}^{-1}$) (RIAN, 2012) and rainfall input during the fallow and growing cycle period (10 kg N ha^{-1}).

The root N:shoot N ratio used for developing the model of Di Ciocco et al. (2011) was 0.32:1, based on Salvagiotti et al. (2008). This ratio fitted well to local data on root production by soybean (Alvarez et al., 2011). These estimations are lower than those of (Rochester et al., 1998) that rounded 0.4:1. Taken into account the later figure N input by soybean fixation would result in an increase of 13%. For the 2006–2010 period, the regional budget for cropped soils would turn from near neutral to $+0.17 \text{ Mt y}^{-1}$ and the budget for all agroecosystems would pass from $+1.34 \text{ Mt y}^{-1}$ to $+1.54 \text{ Mt y}^{-1}$.

Legumes represent a N input that is much more efficient in terms of energy consumption and with less environmental impacts compared to the N input resulting from fertilizer application (Mosier, 2002; Jensen and Hauggaard-Nielsen, 2003). In spite of this, during the 20th Century rotations that included legumes have been replaced by fertilized grain crops around the World (Crews and Peoples, 2004). In the case of the Pampas, legume pastures were replaced by soybean, and resulted in a grain producing agroecosystem that remained highly efficient and with low ecological constraints. The main concern in this present regional scenario could be the small carbon input of soybean, which could have a negative impact on soil organic matter levels in the future (Alvarez et al., 2011).

Average N fertilizer rate applied (2006–2010 period) was 55 kg N ha^{-1} to wheat, 59 kg N ha^{-1} to corn and 32 kg N ha^{-1} to sunflower. Regarding the winter crop wheat, N input from rainfall during fallow and crop growing cycle approximated 8 kg N ha^{-1} . During fallow and crop growing cycle of summer crops this N input was ca. 10 kg N ha^{-1} . These inputs did not balance the N harvested in grains leading to budgets of $+12 \text{ kg N ha}^{-1}$, -10 kg N ha^{-1} , and -6 kg N ha^{-1} , respectively. During the wheat growing cycle agroecosystems received more N than the amount that was harvested but, during corn and sunflower cycles, negative N balances were estimated. As the N budget during the soybean cycle is also

negative, the agricultural phase of rotations is usually a period of N depletion at regional scale in the Pampas.

Nitrogen use efficiency increased in the Pampas during the last 50 years but still a surplus of approximately 40% N exists. This N surplus is similar to the World average surplus (Galloway et al., 2004). Conversely, the proportion of fertilizer N to total input is ca. 14%, which is lower than the World average of 38% or the averages of 50–54% corresponding to Europe and North America (Galloway et al., 2004). Consequently, most of the N input in the Pampas is fixed into living tissues by biological fixation and then transferred to soil organic matter. A lower environmental impact of this organic N may be expected than that from fertilization (Neeteson, 1995). At global scale ca. 35% of N inputs are released to the environment (Eickhout et al., 2006). In the Pampas these mentioned losses may probably be much lower, but possible sinks of this N cannot be addressed for at present because organic N surveys or adequate local models for losses estimation are not available. Our results contrast with a previous one in which N budgets were estimated to be negative in the Pampas using methodologies not developed with local data for N fixation estimation and a lower N input by rainfall was assumed (Viglizzo et al., 2001). This seems to be the main difference between that study and the present one. The generation of local models and coefficients appears to be required for adequate N budget calculations.

5. Conclusions

Cultivated area doubled in the Pampas of Argentina during the last decades due to the replacement of livestock production by the soybean crop. Nitrogen budget of the whole region is positive with an input excess of ca. 40%. When only cropped soils are taken into account the budget is negative under high yielding scenarios with humid climate. Nitrogen use efficiency of pampean agriculture is very high as partial factor productivity of N inputs is 4–6-fold greater than in other grain producing regions of the Word. This result may be attributed to the high efficiency of fixed N in generating biomass compared to fertilizer N.

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