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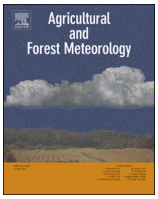

Modelling inter-annual variation in dry matter yield and precipitation use efficiency of perennial pastures and annual forage crops sequences

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ABSTRACT

In livestock systems of the Argentinean Pampas, its forage production stability relies on the integration of two landcovers, annual forage crop sequences and perennial pastures. Despite the key role that these forage cropping systems have on current milk and beef production, it is unclear how year-by-year variability of precipitation affect forage dry matter (DM) yield and precipitation use efficiency (PUE, *i.e.* the quotient between forage DM yield and precipitation). The aims of this study were to analyze the impact (i) of year-by-year precipitation variability on DM yield and PUE of oats-maize (*Avena sativa* L. - *Zea mays* L.) double-crop and alfalfa (*Medicago sativa* L.) and (ii) of cumulative precipitation during the critical period of maize on DM yield and PUE of oats-maize double-crop. We used a modelling approach to estimate DM yield and PUE of oats-maize (sequence) and alfalfa in five locations of the Argentinean Pampas, which differed in annual precipitation (AP) and variability of it. Coefficient of variation (CV) was used as the main statistical variable to compare the variability of AP (CV_{AP}), DM yield (CV_{DM}), and PUE (CV_{PUE}). Mean DM yield of both landcovers was higher in locations with high AP (> 800 mm) than with low AP (< 800 mm). Although alfalfa had lower mean DM yield than sequence in all locations, it showed a lower CV_{DM} than sequence. In contrast, sequence showed lower and higher CV_{DM} than CV_{AP}, depending on location. Moreover, changes in DM yield due to variations of AP were higher in sequence than in alfalfa. On the other hand, mean PUE was higher for sequence (2.2 g DM m^{-2} mm^{-1}) than that of alfalfa (1.6 g DM m^{-2} mm^{-1}). The CV_{PUE} between locations, *i.e.* an index that reflects the spatial variability, ranged from 20 for the sequence to 68% for alfalfa, whereas CV_{PUE} between years, *i.e.* an index that reflects the temporal variability, ranged from 16 to 31 % for both landcovers. Precipitation use efficiency tended to be similar across locations in years with low AP (< 800 mm) compared to years with high AP (> 800 mm). Our results provided valuable knowledge for decision making in livestock systems of this region through the development of spatial and temporal models between DM yield and AP. In a broader sense, they also showed that shifts from perennial to seasonal forage covers increased yields but also its inter-annual variability, posing a risk for farmers.

Abbreviations: APSIM, Agricultural Production Systems Simulator; AFCS, annual forage crop sequences; AP, annual precipitation; BAL, Balcarce; CV_{AP}, coefficient of variation of annual precipitation; CV_{DM}, coefficient of variation of dry matter yield; CV_{PUE}, coefficient of variation of precipitation use efficiency; P_m, cumulative precipitation during the critical period of maize; DM, dry matter; GV, General Villegas; PP, perennial pastures; PER, Pergamino; PUE, precipitation use efficiency; RAF, Rafaela; RD_{AP}, relative deviation of annual precipitation; RD_{DM}, relative deviation of dry matter yield; RD_{PUE}, relative deviation of precipitation use efficiency; TL, Trenque Lauquen

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1. Introduction

There is an increasing interest to integrate cultivated perennial pastures (PP) and annual forage crop sequences (AFCS) to improve the productivity of livestock systems based on direct graze under predicted scenarios of climate change (Chapman et al., 2008, 2011; Harrison et al., 2017; Chang-Fung-Martel et al., 2018). Accordingly, forage production in many livestock systems of the Pampas, in the Rio de la Plata area, are predominantly based on the integration of both, AFCS and PP (Arzadun et al., 2003; Abdelhadi et al., 2004; Arelovich et al., 2011; Ojeda et al., 2016, 2018a, b).

Historically, the feeding base of the Pampas livestock systems has been based on cultivated perennial pastures and natural grasslands (Baldi and Paruelo, 2008). However, in the last 24 years, the sowing area of PP, mainly composed by pure and mixed alfalfa stands (~60–70%), strongly decreased (INDEC, 1988, 2002; FAOSTAT, 2017; Ojeda et al., 2018a, b) driven by the dramatic expansion of agriculture for grain production (Novelli et al., 2013). At the same time, AFCS as a double-crop contributes for 47% of the forage component in the dairy and beef cattle's diet in this region, excluding breeding livestock systems (FAOSTAT, 2017). The main two components of this rotation are oats (*Avena sativa* L.) for grazing or silage and maize (*Zea mays* L.) for silage, which represent 39 and 48%, respectively, of the forage component in the dairy and beef cattle's diet (Opacak, F., personal communication, CACF).

Despite the key role that these forage cropping systems have on current milk and beef production, it is unclear how year-by-year variability of precipitation affect forage dry matter (DM) yield. This analysis is necessary to guide the adoption of management practices oriented to reduce the variability of DM yield facing up the increasing frequency of extreme climate events (Cullen et al., 2009; Keating et al., 2010; Fariña et al., 2013; Pembleton et al., 2016). In this sense, forage cropping systems based on annual crops can be highly dependent on weather variability (*e.g.* precipitation variability), which will make them highly susceptible to extreme climatic events (Moore et al., 2007). Likewise, climate variability has an impact not only on the forage yield of already established annual forage crops but may also impend critical stages like early crop establishment increasing the risk of crop fails (Ojeda et al., 2018a). On the other hand, PP are frequently able to maintain productivity under climatic constraints, given the higher ability to capture water than annual crops (Travis and Reed, 1983; Heichel et al., 1988), mainly due to their perennial growth habit (Fulkerson et al., 2003).

The different nature of PP and AFCS, regarding their ability to resource capture based on their growing habit, should affect its precipitation use efficiency (PUE), *i.e.* annual DM yield per unit of annual precipitation (AP) (Noy-Meir, 1973). The increase of PUE and a reduction of DM yield variability is a core requirement to face up the future scenarios of climate change and increasing demand for livestock outcomes. In this sense, previous efforts have assessed PUE in grain crops (Caviglia et al., 2004; Van Opstal et al., 2011), natural grassland (Paruelo et al., 1999; Bai et al., 2008; Hu et al., 2010) and cultivated forage systems (Ojeda et al., 2018a, 2018b) in several environments. However, the comparison perennial covers *v.* annual covers across locations, under the same environmental features remains poorly understood.

The interaction between production systems and climate variability may strongly affect DM yield and PUE variability, depending on the combination of agronomical management practices and edaphoclimatic conditions. The use of crop simulation models, as a tool to explore a wide range of agronomical management practices across contrasting environments, may sensibly reduce the need of expensive and long-term field experiments (Apipattanavis et al., 2010; Teixeira et al., 2015; Pembleton et al., 2016) to quantify the temporal and spatial patterns of DM yield (Apipattanavis et al., 2010; Pembleton et al., 2016) and PUE (Caviglia et al., 2013).

Recent evaluations of Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) showed the ability of this model to accurately simulate DM yield of forage annual crops and alfalfa in temperate (Pembleton et al., 2011, 2013; Moot et al., 2015; Islam et al., 2015; Ojeda et al., 2016, 2018b) and subtropical environments (Ojeda et al., 2016, 2018b). As a consequence, APSIM appears as a valid tool to analyze the effect of year-by-year precipitation variability on DM yield, and hence PUE, and may allow identifying key strategies to improve PUE, a main component of forage production in the Pampas livestock systems.

Therefore, the aims of this study were to analyze the impact (i) of year-by-year precipitation variability on DM yield and PUE of oats-maize double-crop and alfalfa and (ii) of cumulative precipitation during the critical period of maize on DM yield and PUE of oats-maize double-crop. We used a modelling approach to estimate DM yield and PUE of oats-maize and alfalfa in five locations, with different mean annual precipitation and variability of it, of the Argentinean Pampas.

2. Materials and methods

2.1. Experimental locations and landcovers

Simulated DM yields of an annual sequence and a perennial pasture were obtained for five locations across Argentinean Pampas: Rafaela (RAF) (31°11´S, 61°30´O) in center Santa Fe Province, Pergamino (PER) (33°56´S 60°33´O) in northern Buenos Aires Province, General Villegas (GV) (35°01´S 63°01´O) and Trenque Lauquen (TL) (36°04´S 62°45´O) in northwestern Buenos Aires Province, and Balcarce (BAL) (37°45´S 58°18´O) southeastern Buenos Aires Province. These locations were chosen to cover broad weather conditions of annual precipitation, its inter-annual variability (Table 1), and because are representative of most dairy and beef fattening production systems enclosed in the

Table 1
Annual precipitation and its inter-annual variability for the five chosen locations in the Argentinean Pampas. These locations enclosed the main regional gradient in which dairy and fattening beef production systems are located.

Location	Latitude/Longitude	AP (mm)	CV (%)	AP < 600[a] (%)	AP < 700[a] (%)	AP < 800[a] (%)	Mean cumulative precipitation from 1 September to 1 March[b]		
							Mean (mm)	CV (%)	Minimum–Maximum (mm)
PER	33.9 S/60.5 W	1008	24	0	7	20	627	29	383–1040
RAF	31.2 S/61.5 W	990	21	7	13	17	623	23	377–881
BAL	37.5 S/58.3 W	918	19	0	13	27	535	26	220–800
GV	35.0 S/63.0 W	818	26	10	30	50	536	32	173–971
TL	36.1 S/62.7 W	797	26	23	40	53	511	27	272–840

Abbreviations: RAF, Rafaela; PER Pergamino; GV, General Villegas; TL, Trenque Lauquen; BAL, Balcarce; AP, mean annual precipitation; CV, coefficient of variation.

[a] AP < 600, AP < 700, and AP < 800 represent the percent of years of a 30-year climatic series (1983–2013) with AP less than 600, 700 and 800 mm, respectively.

[b] The calculations were based on a 30-year climatic series (1983–2013).

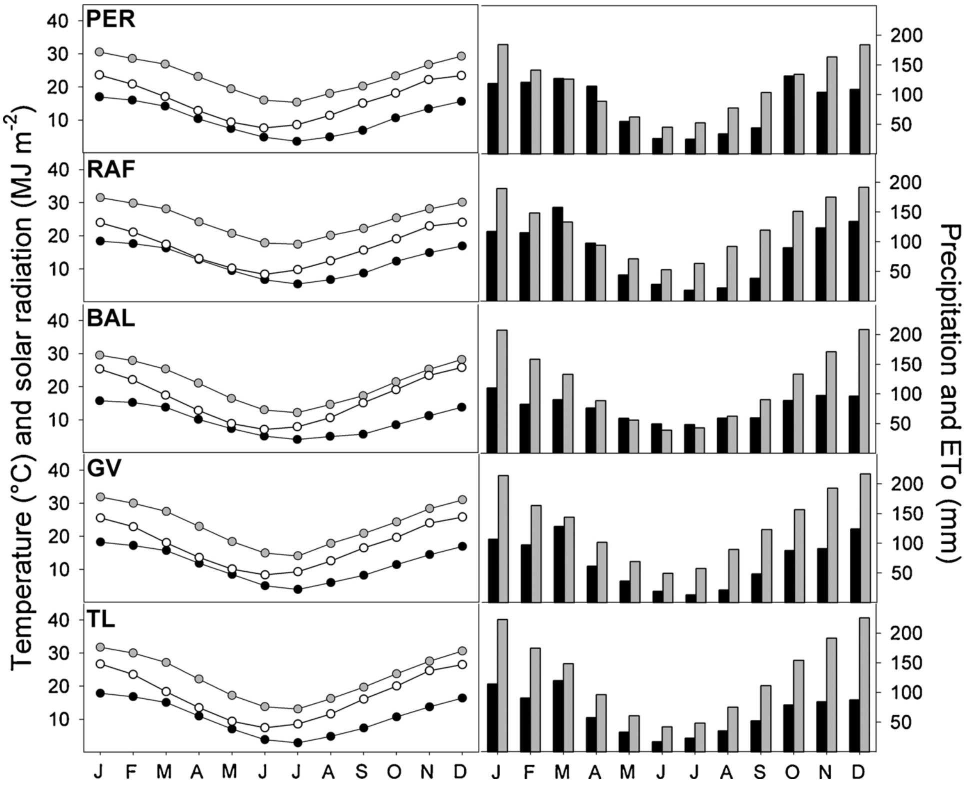

Fig. 1. Mean monthly minimum (line with black circles) and maximum air temperature (line with grey circles), global solar radiation (line with white circles), precipitation (black bars) and Penman potential evapotranspiration (ETo) (grey bars) at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen (TL).

Pampas. We explicitly exclude the Flooding Pampas region, majorly devoted to beef breeding systems based on non-cultivated perennial pastures/grassland. The selected locations showed different inter-annual variation in AP (Table 1). In 17 to 27% of the years, AP was less than 800 mm at RAF, PER and BAL, while in 50 to 53% of the years not exceeded this value at TL and GV (Table 1). Although in < 7% of the years, AP not exceeded 600 mm at RAF, PER and BAL (Table 1), in 10 to 23% of the years, AP was less than this value at TL and GV. On average, 63% of AP was recorded in a six-month period, from 1 September to 1 March (Table 1). However, there were extreme dry years where AP values were very low in the mentioned period (*e.g.* 173, 220 and 272 mm at GV, BAL and TL, respectively) (Table 1).

The simulated annual sequence was oats-maize double-crop while the simulated perennial pasture was alfalfa in a pure stand. The model was previously calibrated and validated to predict, in a continuous simulation across years, DM yield of alfalfa (Ojeda et al., 2016) and oats-maize (Ojeda et al., 2018b) for these environments. Crop growth was simulated by APSIM (version 7.5) over a 30-years period using climate data from 1983 to 2013 in each location (Fig. 1). Oats and maize were simulated using the *APSIM-Oats* module (Peake et al., 2008) and the *APSIM-Maize* module (Carberry et al., 1989), respectively, while alfalfa was simulated using the *APSIM-Lucerne* module (Robertson et al., 2002). All simulations were carried-out under dryland conditions (*i.e.* no-irrigated).

2.2. Model configuration

2.2.1. Climate data

Daily meteorological data (minimum and maximum air temperature, global solar radiation and precipitation) were obtained from a meteorological station at each location. Any missing daily solar radiation, minimum and maximum temperature data were obtained from NASA Prediction of Worldwide Energy Resource (POWER) - Climatology Resource for Agroclimatology (NASA, 2017). Fig. 1 shows a complete climatic seasonal description by location based on historical data (1983–2013). Table 1 shows a precipitation description by location using the same dataset.

2.2.2. Soil data

Soil initial conditions were set through a 10-year APSIM simulation of previous management of alfalfa where location-specific climates and soil data were used (Ojeda et al., 2018b). The simulation outputs from this period were not used in any subsequent analysis.

The *SoilWat* module, one of the two soil water modules available in the APSIM model, was used in this study. This module runs a water balance on a daily-step in which soil evaporation, plant transpiration, drainage, and runoff are included.

2.2.3. Crop growth

Annual crops were simulated in a sequence mode (Ojeda et al., 2018b), *i.e.* in a continuous simulation across years, beginning with oats sown on 1 March 1983. The sowing and harvesting dates were programmed as a sowing window through the *sow using a variable rule* module. This module allows determining an initial and final date for a sowing window, which is determined by the user. The sowing window for oats was from 15 February to 15 March and for maize was from 15 September to 15 October for all locations, except at Balcarce. Due to the delay to achieve minimal soil temperatures to maize growth (~10 °C) in early spring at Balcarce, at this location the sowing window was delayed 15 days, which led to a following delay of 15 days in the sowing of oats. Maize harvesting date was determined at R5 phenological stage (Ritchie and Hanway, 1982) by the *harvesting* module. These dates corresponded with the maize three-quarters milk line stage of maturity and 37% DM content (Cooke and Bernard, 2005), considered optimal for silage. Additionally, to avoid overlap between the growth of maize and the following oats, a harvest management rule at fixed date was added. Thus, irrespective of the phenological stage, a killing date of maize was set on 14 February (except at Balcarce where it was on 28 February) by the *end crop on a fixed date* module. Similar approach was applied to oats harvest on 14 September (except at Balcarce where it was on 30 September). Oat was managed under frequent harvests. The first defoliation was set at 1000 growing degree days (°Cd) (base

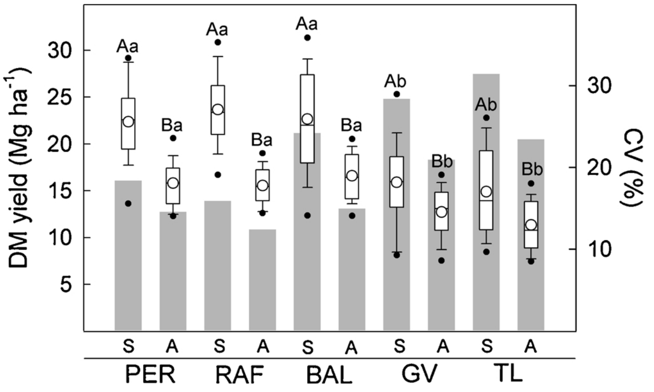

Fig. 2. Mean dry matter (DM) yield of sequence (S) and alfalfa (A) at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen for a 30-year climatic series (1983–2013). Black lines and the white circles inside the boxes represent the median and the mean, respectively. The lower and upper limits of the vertical boxes represent the 25th and 75th percentiles, respectively. The capped lines and the black circles represent the percentiles 10, 90 and 5, 95, respectively. Different upper-case letters indicate significant differences between treatments for the same location ($\alpha = 0.05$). Different lower-case letters indicate significant differences between locations for the same treatment ($\alpha = 0.05$). The grey bars indicate the coefficient of variation (%) of modelled DM yield.

temperature 0 °C), while the following crop defoliations were set with an interval between harvests of 450 °C d, through the *harvesting* module. We did not consider DM yields increases due to breeding effects across years.

Alfalfa was simulated as a perennial crop (*i.e.* sown once at the start of each simulation) during a 4-year crop stand, a reliable persistence in our region. Therefore, alfalfa was consecutively sown 8 times during all simulation period. The alfalfa sowing date was 15 March for all locations. Crop defoliation interval was set to 500 °C d (base temperature 2 °C) irrespective of the season within a year. Also, specific dormancy rules to control the expression of winter dormancy were included as described in Pembleton et al. (2011) and in Ojeda et al. (2016). In all simulation runs, the harvest rule was set to remove the aerial biomass at a height of 0.03 m. A complete description of the management practices used to carry-out the calibration and validation of the model are fully provided in Ojeda et al. (2016) and in Ojeda et al. (2018a,b).

2.3. Analysis of inter-annual variability

Precipitation use efficiency was calculated as the quotient between annual DM yield and AP for all locations. Based on the previous calculations, box-plots of annual DM yield, and PUE over a 30-years period (1983–2013) were compiled for each location and landcovers.

Means for AP, annual DM yield and PUE were calculated as the average of 30-years period for each location. The inter-annual variability of AP, annual DM yield and PUE was characterized using the coefficient of variation (CV). In addition, the relative deviation (RD) in AP, annual DM yield, and PUE was calculated by the following equation:

$$RD_x = (\text{Observed value}_x - \text{Mean value}_x)/\text{Mean value}_x \text{ x } * 100 \qquad (1)$$

where RD is the relative deviation of AP, annual DM yield or PUE and x is AP, annual DM yield or PUE at a given location.

On the other hand, cumulative precipitation during the critical period of maize (P_m) was calculated to analyze the effect of water deficit during this period on DM yield and PUE of sequence. The critical period of maize included 15 days pre- and post silking (R1; Ritchie and Hanway, 1982). The date of this phenological stage was estimated as 800 °C d from crop emergence.

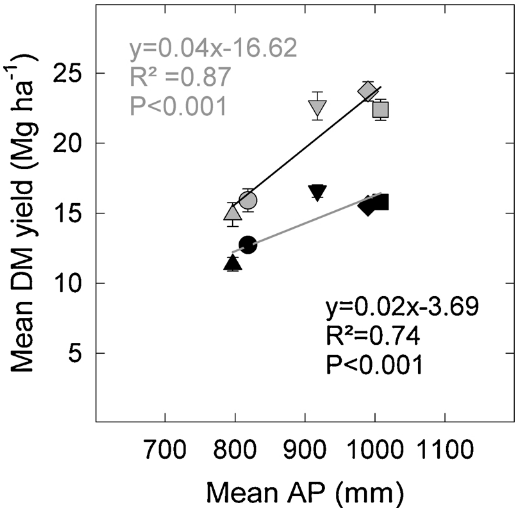

Fig. 3. Mean dry matter (DM) yield *v.* mean annual precipitation (AP) for sequence (grey symbols) and alfalfa (black symbols) at Rafaela (diamond), Pergamino (square), General Villegas (circle), Trenque Lauquen (up triangle) and Balcarce (down triangle) for a 30-year climatic series (1983–2013). The black and grey lines represent the adjusted regression for sequence and alfalfa, respectively. The grey and black equations, R^2 and P-values correspond to sequence and alfalfa, respectively.

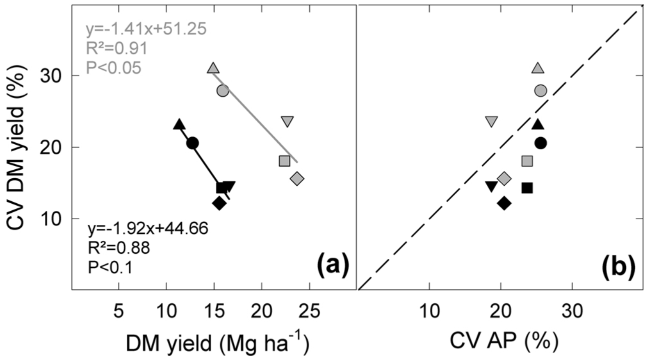

Fig. 4. Scatter plots between coefficient of variation (CV) of mean dry matter (DM) yield *v.* (a) DM yield and (b) CV of annual precipitation for sequence (grey symbols) and alfalfa (black symbols) at Rafaela (diamond), Pergamino (square), General Villegas (circle), Trenque Lauquen (up triangle) and Balcarce (down triangle) for a 30-year climatic series (1983–2013). In panel a, grey and black lines represent the adjusted regression for sequence and alfalfa, respectively. The grey and black equations, R^2 and P-values correspond to sequence and alfalfa, respectively. In panel b, diagonal line represents the adjusted line 1:1 (*i.e.* y = x).

2.4. Statistical analysis

A specific statistical analysis was carried-out when correlation between variables was not independent (*i.e.* a spurious correlation). First, when the correlation included Y/X and X variables (*i.e.* CV_{DM} *v.* DM yield and PUE *v.* AP), the Pearson correlation coefficient (*r*) was calculated through an alternative equation that allow correcting the spurious correlation. Thus, this calculation was performed according to the equation by Brett (2004):

$$r = -CV_X/(CV_Y^2 + CV_X^2)^{1/2} \qquad (2)$$

where CV_X is the CV of DM yield or CV of AP and CV_Y is the CV of standard deviation of DM yield or CV of DM yield for each landcover.

The results of these analyses were presented using the coefficient of determination (R^2) calculated as the square of r.

Associations between variables were evaluated using linear and

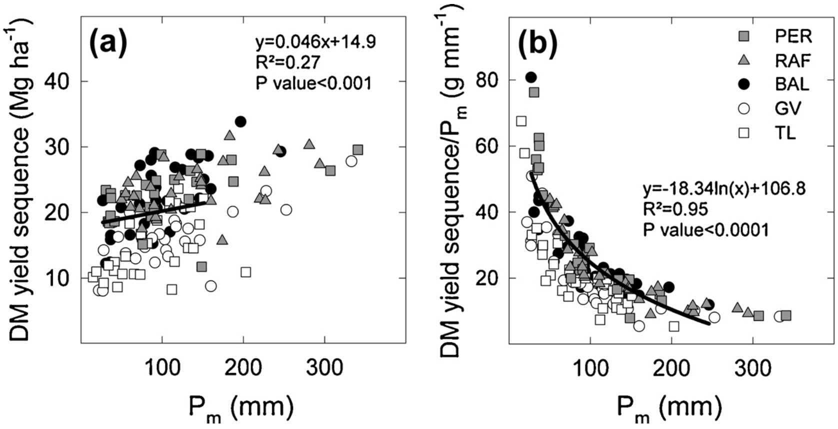

Fig. 5. (a) Dry matter (DM) yield of sequence and (b) ratio of DM yield of sequence and cumulative precipitation during the critical period of maize (P_m) *v.* P_m at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen (TL) for a 30-year climatic series (1983–2013). The lines represent the adjusted regressions to the complete data set (n = 150). The regression equations for each location are provided in Table 2.

Table 2

Statistical summary of DM yield of sequence (DM yield seq) and ratio between DM yield of sequence and cumulative precipitation during the critical period of maize (DM yield of sequence /P_m) *v.* cumulative precipitation during the critical period of maize (P_m) at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen (TL).

	PER	*RAF*	*BAL*	*GV*	*TL*
No. Obs.	30	30	30	30	30
DM yield seq v. P_m					
R^2	0.250	0.225	0.471	0.479	0.267
Regression equation	y = 0.0272x + 19.667	y = 0.0256x + 20.212	y = 0.0734x + 15.201	y = 0.044x + 11.267	y = 0.0522x + 10.358
P value	0.007	0.008	< 0.001	< 0.001	0.003
DM yield seq /P_m v. P_m					
R^2	0.845	0.861	0.715	0.765	0.783
Regression equation	y = −25.4ln(x) + 143.9	y = −18.6ln(x) + 110.8	y = −20.6ln(x) +119.7	y = −14.5ln(x) + 85.2	y = −18.2ln(x) + 100.4
P value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

non-linear regressions and correlation analysis. All statistical analyses were carried-out in R (version 2.3-0) through the Rcmdr package (Fox et al., 2017).

3. Results

3.1. DM yield

Mean annual DM yield ranged between 11.4 to 16.6 Mg ha^{-1} for alfalfa and from 14.9 to 23.7 Mg ha^{-1} for sequence (Fig. 2). The maximum DM yields of sequence were observed at BAL (33.8 Mg ha^{-1}) and for alfalfa at PER (21.3 Mg ha^{-1}), while the minimum DM yields for both landcovers were observed at GV (8.1 Mg ha^{-1} for sequence and 6.5 Mg ha^{-1} for alfalfa; Fig. 2).

Across locations, the mean increment of DM yield per unit of annual precipitation was 0.02 and 0.04 Mg ha^{-1} mm^{-1} for alfalfa and sequence, respectively (Fig. 3).

There was a negative association ($P < 0.001$) between CV_{DM} of both, alfalfa and sequence, and DM yield (Fig. 4a), but there was no association ($P > 0.1$) between CV_{DM} and CV_{AP} for either types of landcover (Fig. 4b). However, CV_{DM} of alfalfa was lower than CV_{AP} for all locations (Fig. 4b) while CV_{DM} of sequence was higher than CV_{AP} at three out of five locations (Fig. 4b). Moreover, the range of variability quantified by CV, was wider for DM yield (12.2–30.9 %) than for AP (18.7–25.6%) (Fig. 4b). It should be noted that locations with low mean AP values showed high CV_{AP} (GV and TL) (Table 1).

Within the sequence, maize accounted for 95% of variability of DM yield of it ($R^2 = 0.95$; $P < 0.001$), while oats and sequence DM yields were unrelated ($P = 0.57$). Although mean DM yield of maize was 15.9 Mg ha^{-1}, it varied considerably depending on AP and location. For example, and similar than for sequence, the maximum and minimum maize DM yields were recorded at BAL (29.6 Mg ha^{-1}) and GV (0 Mg ha^{-1}) with an AP of 1232 and 280 mm, respectively. Although mean DM yield of oats (4 Mg ha^{-1}) was a quarter of DM yield of maize, it showed a much lower mean CV_{DM} than maize (28% *v.* 38%). Moreover, DM yield of maize was directly associated with AP ($R^2 = 0.46$; $P < 0.001$), but there was no association between DM yield of oats and AP ($P = 0.77$). In fact, sequence DM yield was strongly associated with cumulative precipitation during the critical period of maize (P_m; Fig. 5a; Table 2). Moreover, there was a convergence response among locations in the association between DM yield and P_m (Fig. 5a). In dry years, *i.e.* with low P_m (< 100 mm), locations situated in the extreme wet end of the AP gradient (Table 1), showed higher DM yields than those in the lower end of it (Fig. 5a), while in wet years, *i.e.* with high P_m (> 100 mm), DM yields converge to similar values (Fig. 5a). As a consequence, for P_m values above ~100 mm, DM yield of sequence did not increase significantly per unit of P_m (Fig. 5b).

The inter-annual response of DM yield to AP revealed a better fit for sequence than for alfalfa in all locations, except at TL (Fig. 6a). Between landcovers, sequence had a higher slope than alfalfa (Fig. 6a) across locations. Moreover, and for the sequence, the slope increased as mean annual precipitation decreased (Fig. 6a).

Likewise, RD_{DM} was strongly associated with RD_{AP} (Fig. 6b). Particularly, RD_{DM} and RD_{AP} were more associated in locations with low AP (< 800 mm) than in locations with high AP (> 800 mm) (Fig. 6b). Also, RD_{DM} increases per unit of RD_{AP} were remarkably higher for sequence than for alfalfa in locations with high AP, while this relationship tends to be similar between landcovers in locations with low AP (Fig. 6b).

3.2. Precipitation use efficiency

On average, PUE was higher for sequence (2.2 g m^{-2} mm^{-1}) than for alfalfa (1.6 g m^{-2} mm^{-1}) (Fig. 7), except at GV and TL. The maximum and minimum PUE values of sequence were recorded at GV (4.3 and 1.0 g m^{-2} mm^{-1}, respectively), while for alfalfa it was recorded at

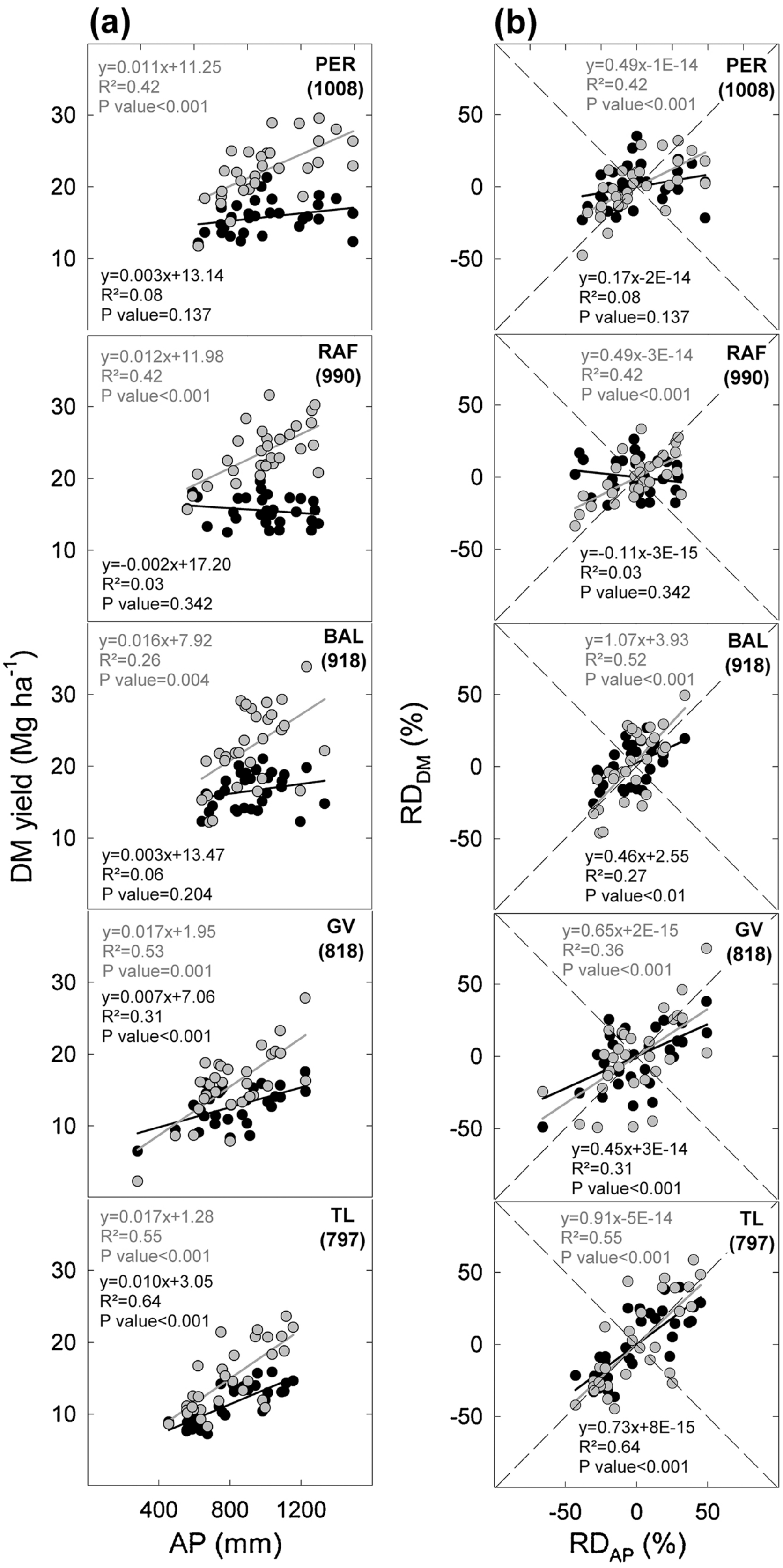

Fig. 6. (a) Dry matter (DM) yield *v.* annual precipitation (AP) and (b) relative deviation of DM yield (RD_{DM}) *v.* relative deviation of AP (RD_{AP}) of sequence (grey circles) and alfalfa (black circles) at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen (TL) for a 30-year climatic series (1983–2013). The grey and black line represents the adjusted regression for sequence and alfalfa, respectively. The grey and black equation, R^2 and P value correspond to sequence and alfalfa, respectively. The dashed lines represent a deviation value of DM yield = 0. The number below location name indicates the annual precipitation in mm.

RAF ($3.1\ g\ m^{-2}\ mm^{-1}$) and PER ($0.8\ g\ m^{-2}\ mm^{-1}$), respectively (Fig. 7).

The regression analysis of PUE *v.* AP revealed a negative association ($P < 0.001$) for both landcovers (alfalfa and sequence) (Fig. 8a). However, its sensitivity was not similar. For example, in GV as AP increased both landcovers tended to have similar PUE values, while in BAL and RAF the opposite occurred (Fig. 8a). Likewise, the RD_{PUE} was negatively associated with RD_{AP} across locations, except at TL and for

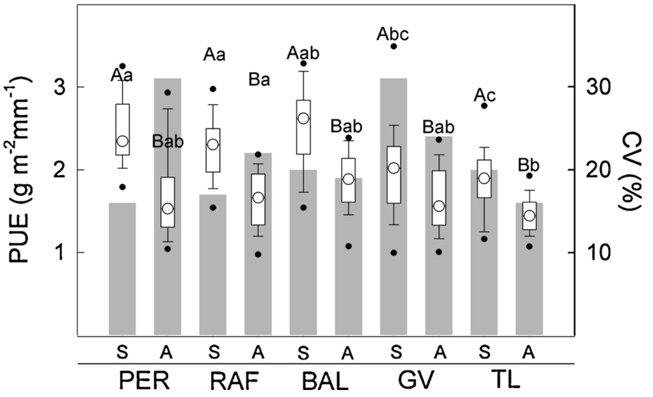

Fig. 7. Mean precipitation use efficiency (PUE) of sequence (S) and alfalfa (A) at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen (TL) for a 30-year climatic series (1983–2013). Black lines and the white circles inside the boxes represent the median and the mean, respectively. The lower and upper limits of the vertical boxes represent the 25th and 75th percentiles, respectively. The capped lines and the black circles represent the percentiles 10, 90 and 5, 95, respectively. Different upper-case letters indicate significant differences between treatments for the same location ($\alpha = 0.05$). Different lower-case letters indicate significant differences between locations for the same treatment ($\alpha = 0.05$). The grey bars indicate the coefficient of variation (%) of modelled DM yield.

sequence at BAL ($P < 0.001$; Fig. 8b). Contrarily to RD_{DM}, RD_{PUE} decreases per unit of RD_{AP} were remarkably higher for alfalfa than for sequence in locations with high AP (> 800 mm), while this relationship tends to be similar between landcovers in locations with low AP (< 800 mm; Fig. 8b).

4. Discussion

The aims of this study were to analyze the impact (i) of year-by-year precipitation variability on DM yield and PUE of oats-maize double-crop and alfalfa and (ii) of cumulative precipitation during the critical period of maize on DM yield and PUE of oats-maize double-crop. Overall, our results showed that shifts from perennial to seasonal forage covers increased DM yields but also its inter-annual variability.

4.1. Stability of DM yields as a function of annual precipitation

As was anticipated, our results showed that mean DM yield of both landcovers was higher in locations with high AP than with low AP (Fig. 2). Although alfalfa had lower mean DM yield than sequence in all locations (Figs. 3; 4a), perennial landcover showed a higher stability (lower inter-annual CV_{DM}) than sequence landcover, when compared to AP variability (Fig. 4b). In contrast, sequence showed alternatively lower and higher variability than precipitation (Fig. 4b), depending on mean AP in each location. The lower inter-annual CV_{DM} of alfalfa could be explained due to its perennial growth habit, which provides higher capacity to capture water and solar radiation compared to annual crops (Nosetto et al., 2015). Besides, its deep root system and the capability to accumulate high levels of water-soluble carbohydrate in storage organs (crown) makes it resilient to droughts (Annicchiarico et al., 2013). On the other hand, sequence must go through, at least, two annual establishment periods, *i.e.* period between sowing to critical canopy cover, in which resource capture is limited (Ojeda et al., 2018a). Thus, our results demonstrated that the use of a crop sequence was a needed requirement to maximize DM yield though it decreased DM yield stability. Likewise, the results of alfalfa are similar for those observed by Durante et al. (2017) for cultivated perennial pastures (typically composed by alfalfa, *Festuca arundinacea* Schreb., *Dactylis glomerata* L., *Trifolium pratense* L., and *Trifolium repens* L.) in the Flooding Pampas. Besides, these authors found that CV_{DM} of natural grasslands was lower than that of cultivated pastures. These differences could be associated with higher risk of adverse climatic conditions in cultivated pastures during their mandatory establishment periods (Ojeda et al., 2018a) in contrast to continuous natural grassland cover. Moreover, cultivated landcovers have lower species diversity, a key mechanism for stability (McNaughton, 1977), than natural grasslands. In addition, it may be exacerbated in landcovers based on annual crops which almost double the inter-annual variability from that of natural grasslands (Durante et al., 2017).

On the other hand, the CV of cumulative precipitation from 1 September to 1 March, *i.e.* the period with higher crop growth rates, ranged from 23 to 32% between locations (Table 1). Nevertheless, at TL and GV, in more than 50% of the years AP was less than 800 mm (Table 1) and only 65% of AP (< 550 mm) occurred between September and March. Also, in these locations the highest CV_{AP} values were recorded (Table 1). As a result, lower AP and higher CV_{AP} led to lowest DM yields at GV and TL. These results highlight the importance to implement agronomic strategies to decrease the variability of DM yield, *i.e.* < CV_{DM}.

4.2. Precipitation use efficiency

Our results showed that mean PUE was higher for sequence (2.2 g DM m^{-2} mm^{-1}) than that of alfalfa (1.6 g DM m^{-2} mm^{-1}) in all locations (Fig. 7). This difference could be attributed to the inclusion of maize in the sequence, which has an intrinsically higher PUE than alfalfa (Ojeda et al., 2018a). The higher PUE in C4 species, such as maize, than in C3 species, such as alfalfa, is related to the efficiency of the photosynthetic pathway inherent to each crop (*e.g.* Sinclair and Muchow, 1999). Although there were differences of PUE between locations for sequence ($P < 0.05$; Fig. 7), there were no differences for alfalfa, except between RAF and TL ($P > 0.05$; Fig. 7). In general, the recorded values of PUE were consistent with previous experimental estimations (*e.g.* Caviglia et al., 2004; Turner, 2004; Turner and Asseng, 2005; Van Opstal et al., 2011; Caviglia et al., 2013). However, unlike these studies, our model simulations were carried-out over a wider temporal (*e.g.* climate historical records) and spatial range. Moreover, average PUE of alfalfa was slightly higher than that from un-grazed natural grassland from the U.S. Northern mixed prairies (*i.e.* 1.25 g m^2 mm; Irisarri et al., 2016).

Several studies have reported functions of DM *v.* AP yield for many landcover types to assess DM yield variability at spatial (*e.g.* Sala et al., 1988; Ojeda et al., 2017), temporal (Smith et al., 2007; Irisarri et al., 2016) and both scales (*e.g.* Lauenroth and Sala, 1992; Paruelo et al., 1999; Bai et al., 2008; Hu et al., 2010; Durante et al., 2017). In this study, we reported DM yield responses of (i) a set of different locations to spatial patterns in AP (spatial model; Fig. 3) and (ii) a single location to a time-series of precipitation (temporal model; Fig. 6a). The CV_{PUE} between locations, *i.e.* an index that reflects the spatial variability, ranged from 20 for the sequence to 68% for alfalfa, whereas CV_{PUE} between years, *i.e.* an index that reflects the temporal variability, ranged from 16 to 31 % for both landcovers. Also, differences between spatial and temporal variability were smaller during years with low AP (< 800 mm) (Figs. 3; 6a). On the other hand, DM yield of grassland and cultivated perennial pastures have been more stables than forage or grain annual crops in the face of AP variations. For example, Lauenroth and Sala (1992) associated the differences between spatial and temporal PUE variations to vegetation structure evaluating a long-term DM yield of grasslands in North U.S. In fact, we showed here that changes in DM yield due to variations of AP were higher in sequence than in alfalfa (Fig. 6a). Also, we reported a strong positive correlation between DM yield and AP in sequence, mainly associated with maize as the main component. These results confirm the strong dependence of annual DM yield due to maize sensitivity to the occurrence of water stress during its critical period (Andrade, 1995) (Fig. 5).

A negative correlation was detected for PUE *v.* AP in all locations

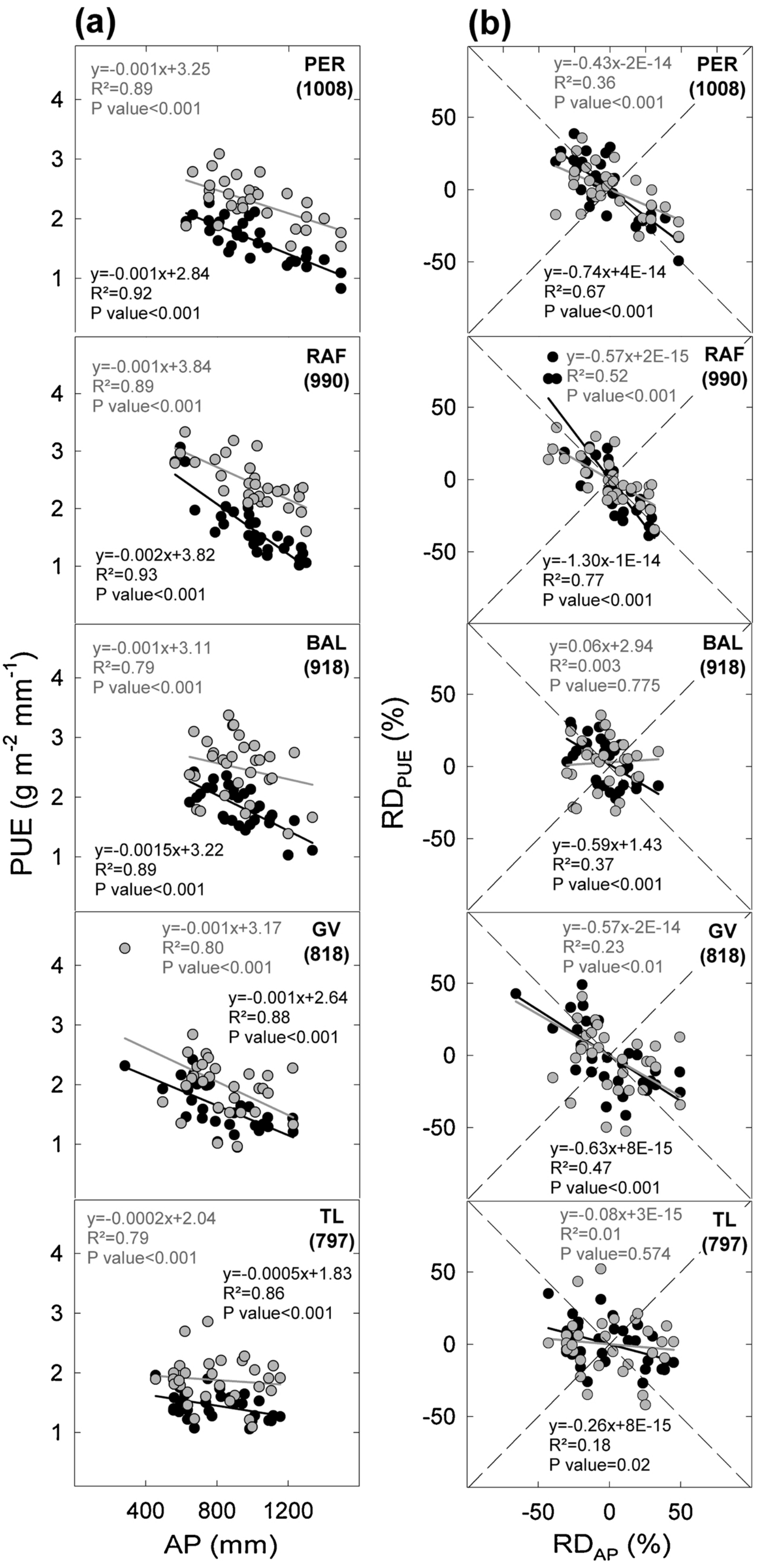

Fig. 8. (a) Precipitation use efficiency (PUE) *v.* annual precipitation (AP) and (b) relative deviation of PUE (RD_{PUE}) *v.* relative deviation of AP (RD_{AP}) of sequence (grey circles) and alfalfa (black circles) at Pergamino (PER), Rafaela (RAF), Balcarce (BAL), General Villegas (GV) and Trenque Lauquen (TL) for a 30-year climatic series (1983–2013). The grey and black line represents the adjusted regression for sequence and alfalfa, respectively. The grey and black equation, R^2 and P value correspond to sequence and alfalfa, respectively. The dashed lines represent a deviation value of PUE = 0. The number below location name indicates the annual precipitation in mm.

(Fig. 8a). Remarkably, PUE was similar for both landcovers during years with low AP at GV and TL. This would indicate that, despite existing differences of DM yield between locations, if productivity is expressed per unit of available water, *i.e.* PUE, the conclusions that can be reached may differ depending on inter-annual AP variations (Fig. 8a). Accordingly, Huxman et al. (2004) showed that PUE of natural grasslands decreased as AP increased for 14 locations across America. However, during dry years, there was a convergence of PUE to a common maximum across landcovers. In fact, in years when water is highly limiting, different locations, with different mean annual precipitation, may have similar PUE. These results are similar to our findings, mainly in the conservativeness of PUE for alfalfa across environments of the Argentinean Pampas (Fig. 8a). Furthermore, it highlights the *lag* effect reported across different perennial landcovers of the world (Oesterheld et al., 2001; Wiegand et al., 2004; Verón et al., 2005). In fact, this *lag* effect indicates that current DM yield is not only associated with AP of the current year, but also with the AP of the previous year.

Collectively our results indicate that to achieve a high PUE in livestock production systems in our region, the focus should be on complement high DM yields with low temporal variability. Simulation models should be useful to provide some of the answers. For example, how the increase of landcover diversity (Pacín and Oesterheld, 2014) sustains the economic output, or even increase it under adverse climatic scenarios. Our results highlighted a differential role of landcovers whether to provide high resource productivity, such as oats-maize double crop, or to improve the forage systems stability, such as alfalfa. Nevertheless, future modelling studies should be focused on identify the optimum sown area of each landcover for a given farm that allows to reach the high PUE with the low inter-annual variability. Likewise, further modelling analysis under future climate scenarios is required to generate predictions of inter-annual variability of PUE for diverse forage systems in the Argentinean Pampas and worldwide.

5. Conclusions

The used framework in this study allowed us to explain a vast portion of the spatial and temporal variation on DM yield and PUE for two contrasting forage covers, oats-maize and alfalfa, in a wide range of edaphoclimatic environments across the Argentinean Pampas. The results presented in this work also provide valuable knowledge for decision making in livestock systems of this region by the development of spatial and temporal models between DM yield and AP.

We quantified, for the first time, how the type of landcover can highly affect forage DM yield and PUE depending on environment. Although alfalfa had lower mean DM yield than sequence in all locations, perennial landcover showed a higher stability than sequence landcover, when compared to AP variability. This suggests that the use of an annual forage system as oats-maize double-crop leads to increments of variability in DM yield and PUE in the long-term. Likewise, annual forage systems face an extra risk to their success just because of the reduced time window during which consecutive annual crops need to get sown and established. In addition, there are increased risks of soil erosion, as well as eventually higher labor costs. Therefore, to achieve high levels of PUE, future agronomic challenges should be focus on maintain a balance between the increments of DM yield production reducing climate and environmental risks.

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References

Abdelhadi, L.O., Lyons, T.P., Jacques, K.A., 2004. Evaluating inoculants for forage crops in Argentine beef and milk grazing systems: effects on silage quality and system profitability. In: Lyons, T.P., Jacques, K.A. (Eds.), Nutritional Biotechnology in the Feed and Food Industries, Alltech 20th Annual Symposium. Nicholasville, KY, USA. pp. 171–177.

Andrade, F., 1995. Analysis of growth and yield of maize, sunflower and soybean grown at Balcarce, Argentina. Field Crops Res. 41, 1–12. http://dx.doi.org/10.1016/0378-4290(94)00107-N.

Annicchiarico, P., Pecetti, L., Tava, A., 2013. Physiological and morphological traits associated with adaptation of lucerne (*Medicago sativa*) to severely drought-stressed and to irrigated environments. Ann. Appl. Biol. 162, 27–40. http://dx.doi.org/10.1111/j.1744-7348.2012.00576.x.

Apipattanavis, S., Bert, F., Podesta, G., Rajagopalan, B., 2010. Linking weather generators and crop models for assessment of climate forecast outcomes. Agr. For. Meteorol. 150, 166–174. http://dx.doi.org/10.1016/j.agrformet.2009.09.012.

Arelovich, H.M., Bravo, R.D., Martínez, M.F., 2011. Development, characteristics, and trends for beef cattle production in Argentina. Anim. Front. 1, 37–45. http://dx.doi.org/10.2527/af.2011-0021.

Arzadun, M.J., Arroquy, J.I., Laborde, H.E., Brevedan, R.E., 2003. Grazing pressure on beef and grain production of dual-purpose wheat in Argentina. Agron. J. 95, 1157–1162. http://dx.doi.org/10.2134/agronj2003.1157.

Bai, Y., Wu, J., Xing, Q., Pan, Q., Huang, J., Yang, D., Han, X., 2008. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology 89, 2140–2153. http://dx.doi.org/10.1890/07-0992.1.

Baldi, G., Paruelo, J., 2008. Land-use and land cover dynamics in South American temperate grasslands. Ecol. Soc. 13. http://www.ecologyandsociety.org/vol13/iss2/art6/.

Brett, M.T., 2004. When is a correlation between non-independent variables "spurious"? Oikos 105, 647–656. http://dx.doi.org/10.1111/j.0030-1299.2004.12777.x.

Carberry, P.S., Muchow, R.C., Mccown, R.L., 1989. Testing the CERES-Maize simulation model in a semi-arid tropical environment. Field Crops Res. 20, 297–315. http://dx.doi.org/10.1016/0378-4290(89)90072-5.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2004. Intensification of agriculture in the south-eastern Pampas: I. Capture and efficiency in the use of water and radiation in double-cropped wheat-soybean. Field Crops Res. 87, 117–129. http://dx.doi.org/10.1016/j.fcr.2003.10.002.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2013. Modelling long-term effects of cropping intensification reveals increased water and radiation productivity in the south-eastern Pampas. Field Crops Res. 149, 300–311. http://dx.doi.org/10.1016/j.fcr.2013.05.003.

Chang-Fung-Martel, J., Harrison, M.T., Rawnsley, R., Smith, A.P., Meinke, H., 2018. The impact of extreme climatic events on pasture-based dairy systems: a review. Crop Pasture Sci. 68, 1158–1169. http://dx.doi.org/10.1071/CP16394.

Chapman, D.F., Kenny, S.N., Beca, D., Johnson, I.R., 2008. Pasture and crop options for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. Agric. Syst. 97, 108–125. http://dx.doi.org/10.1016/j.agsy.2008.02.001.

Chapman, D.F., Kenny, S.N., Lane, N., 2011. Pasture and forage crop systems for non-irrigated dairy farms in southern Australia: 3. Estimated economic value of additional home-grown feed. Agric. Syst. 104, 589–599. http://dx.doi.org/10.1016/j.agsy.2011.06.001.

Cooke, K.M., Bernard, J.K., 2005. Effect of length of cut and kernel processing on use of corn silage by lactating dairy cows. J. Dairy Sci. 88, 310–316. http://dx.doi.org/10.3168/jds.S0022-0302(05)72689-8.

Cullen, B.R., Eckard, R.J., Mason, W., Rawnsley, R.P., 2009. Incorporating changes in daily rainfall characteristics into future climate scenarios. In: Proceedings of the 18th World IMACS/MODISM Congress. Cairns, Australia. pp. 2727–2733.

Durante, M., Piñeiro, G., Irisarri, J.G.N., Oesterheld, M., 2017. Primary production of lowland natural grasslands and upland sown pastures across a narrow climatic gradient. Ecosystems 20, 543–552. http://dx.doi.org/10.1007/s10021-016-0039-2.

FAOSTAT, 2017. Food and Agriculture Data. (Accessed 10 May 2017). http://faostat.fao.org/beta/en/#home/.

Fariña, S.R., Alford, A., Garcia, S.C., Fulkerson, W.J., 2013. An integrated assessment of business risk for pasture-based dairy farm systems intensification. Agric. Syst. 115, 10–20. http://dx.doi.org/10.1016/j.agsy.2012.10.003.

Fox, J., 2017. Using the R Commander: A Point-and-Click Interface for R. Chapman & Hall/CRC Press, Boca Raton FL.

Fulkerson, W.J., Slack, K., Bryant, R., Wilson, F., 2003. Selection for more persistent perennial ryegrass (Lolium perenne) cultivars for subtropical/warm temperate dairy regions of Australia. Aust. J. Exp. Agric. 43, 1083–1091. http://dx.doi.org/10.1071/EA02107.

Harrison, M.T., Cullen, B.R., Armstrong, D., 2017. Management options for dairy farms under climate change: effects of intensification, adaptation and simplification on pastures, milk production and profitability. Agric. Syst. 155, 19–32. http://dx.doi.org/10.1016/j.agsy.2017.04.003.

Heichel, G.H., Delaney, R.H., Cralle, H.T., 1988. Carbon assimilation, portioning and utilization. In: In: Hanson, A.A., Barnes, D.K., Hill JrR.R. (Eds.), Alfalfa and Alfalfa Improvement, vol. 29. American Society of Agronomy, Madison, USA, pp. 195–228.

Hu, Z., Yu, G., Fan, J., Zhong, H., Wang, S., Li, S., 2010. Precipitation-use efficiency along a 4500-km grassland transect. Global Ecol. Biogeogr. 19, 842–851. http://dx.doi.org/10.1111/j.1466-8238.2010.00564.x.

Huxman, T.E., et al., 2004. Convergence across biomes to a common rain-use efficiency. Nature 429, 651–654. http://dx.doi.org/10.1038/nature02561.

INDEC, 1988. Censo Nacional Agropecuario. Resultados Generales. Instituto Nacional de Estadísticas y Censos. Ministerio de Economía, Buenos Aires, Argentina 152 p.

INDEC, 2002. Censo Nacional Agropecuario. Resultados Generales Ampliados. Instituto Nacional de Estadísticas y Censos, Buenos Aires, Argentina 15 p.

Irisarri, J.G.N., Derner, J.D., Porensky, L.M., Augustine, D.J., Reeves, J.L., Mueller, K.E., 2016. Grazing intensity differentially regulates ANPP response to precipitation in North American semiarid grasslands. Ecol. Appl. 26, 1370–1380. http://dx.doi.org/10.1890/15-1332.

Islam, M.R., Garcia, S.C., Clark, C.E.F., Kerrisk, K.L., 2015. Modelling pasture-based automatic milking system herds: grazeable forage options. Asian Australas. J. Anim. Sci. 28, 703–715. http://dx.doi.org/10.5713/ajas.14.0384.

Keating, B.A., et al., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288. http://dx.doi.org/10.1016/S1161-0301(02)00108-9.

Keating, B.A., Carberry, P.S., Bindraban, P.S., Asseng, S., Meinke, H., Dixon, J., 2010. Eco-efficient agriculture: concepts, challenges, and opportunities. Crop Sci. 50, 109–119. http://dx.doi.org/10.2135/cropsci2009.10.0594.

Lauenroth, W.K., Sala, O.E., 1992. Long-term forage production of North American shortgrass steppe. Ecol. Appl. 2, 397–403. http://dx.doi.org/10.2307/1941874.

McNaughton, S.J., 1977. Diversity and stability of ecological communities: a comment on the role of empiricism in ecology. Am. Nat. 111, 515–525. http://dx.doi.org/10.1086/283181.

Moore, A.D., Holzworth, D.P., Hermann, N.I., Huth, N.I., Robertson, M.J., 2007. The common modelling protocol: a hierarchical framework for simulation of agricultural and environmental systems. Agric. Syst. 95, 37–48. http://dx.doi.org/10.1016/j.agsy.2007.03.006.

Moot, D.J., Hargreaves, J., Brown, H.E., Teixeira, E.I., 2015. Calibration of the APSIM-Lucerne model for 'Grasslands Kaituna' lucerne crops grown in New Zealand. J. Agric. Res. 58, 190–202. http://dx.doi.org/10.1080/00288233.2015.1018392.

NASA, 2017. Prediction of Worldwide Energy Resource. (Accessed 20 June 2017). http://power.larc.nasa.gov.

Nosetto, M.D., Paez, R.A., Ballesteros, S.I., Jobbágy, E.G., 2015. Higher water-table levels and flooding risk under grain vs. livestock production systems in the subhumid plains of the Pampas. Agric. Ecosyst. Environ. 206, 60–70. http://dx.doi.org/10.1016/j.agee.2015.03.009.

Novelli, L.E., Caviglia, O.P., Wilson, M.G., Sasal, M.C., 2013. Land use intensity and cropping sequence effects on aggregate stability and C storage in a Vertisol and a Mollisol. Geoderma 195, 260–267. http://dx.doi.org/10.1016/j.geoderma.2012.12.013.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annu. Rev. Ecol. Syst. 4, 25–51. http://dx.doi.org/10.1146/annurev.es.04.110173.000325.

Oesterheld, M., Loreti, J., Semmartin, M., Sala, O.E., 2001. Inter-annual variation in primary production of a semi-arid grassland related to previous-year production. J. Veg. Sci. 12, 137–142. http://dx.doi.org/10.1111/j.1654-1103.2001.tb02624.x.

Ojeda, J.J., Pembleton, K.G., Islam, M.R., Agnusdei, M.G., Garcia, S.C., 2016. Evaluation of the agricultural production systems simulator simulating Lucerne and annual ryegrass dry matter yield in the Argentine Pampas and south-eastern Australia. Agric. Syst. 143, 61–75. http://dx.doi.org/10.1016/j.agsy.2015.12.005.

Ojeda, J.J., Volenec, J.J., Brouder, S.M., Caviglia, O.P., Agnusdei, M.G., 2017. Evaluation of agricultural production systems simulator (APSIM) as yield predictor of *Panicum virgatum* and *Miscanthus* x *giganteus* in several US environments. GCB Bioenergy 9, 796–816. http://dx.doi.org/10.1111/gcbb.12384.

Ojeda, J.J., Caviglia, O.P., Agnusdei, M.G., Errecart, P.M., 2018a. Forage yield, water-and solar radiation-productivities of perennial pastures and annual crops sequences in the south-eastern Pampas of Argentina. Field Crops Res. 221, 19–31. http://dx.doi.org/10.1016/j.fcr.2018.02.010.

Ojeda, J.J., Pembleton, K.G., Caviglia, O.P., Islam, M.R., Agnusdei, M.G., Garcia, S.C., 2018b. Modelling dry matter yield and water productivity of forage crops sequences in the Argentinian Pampas. Eur. J. Agron. 92, 84–96. http://dx.doi.org/10.1016/j.eja.2017.10.004.

Pacín, F., Oesterheld, M., 2014. In-farm diversity stabilizes return on capital in Argentine agro-ecosystems. Agric. Syst. 124, 51–59. http://dx.doi.org/10.1016/j.agsy.2013.10.008.

Paruelo, J.M., Lauenroth, W.K., Burke, I.C., Sala, O.E., 1999. Grassland precipitation-use efficiency varies across a resource gradient. Ecosystems 2, 64–68. http://dx.doi.org/10.1007/s100219900058.

Peake, A., Whitbread, A., Davoren, B., Braun, J., Limpus, S., 2008. The development of a model in APSIM for the simulation of grazing oats and oaten hay. In: Unkovich, M. (Ed.), Global Issues. Paddock Action. Proceedings of 14th Agronomy Conference. Adelaide, Australia.

Pembleton, K.G., Rawnsley, R.P., Donaghy, D.J., 2011. Yield and water-use efficiency of contrasting lucerne genotypes grown in a cool temperate environment. Crop Pasture Sci. 62, 610–623. http://dx.doi.org/10.1071/CP11094.

Pembleton, K.G., Rawnsley, R.P., Jacobs, J.L., Mickan, F.J., O'brien, G.N., Cullen, B.R., Ramilan, T., 2013. Evaluating the accuracy of the agricultural production systems simulator (APSIM) simulating growth, development, and herbage nutritive characteristics of forage crops grown in the south-eastern dairy regions of Australia. Crop Pasture Sci. 64, 147–164. http://dx.doi.org/10.1071/CP12372.

Pembleton, K.G., Cullen, B.R., Rawnsley, R.P., Harrison, M.T., Ramilan, T., 2016. Modelling the resilience of forage crop production to future climate change in the dairy regions of Southeastern Australia using APSIM. J. Agric. Sci. 154, 1131–1152. http://dx.doi.org/10.1017/S0021859615001185.

Ritchie, S.W., Hanway, J.J., 1982. How a Corn Plant Develops, vol. 48 Iowa State University, Cooperative Extension Service, Ames, IA, USA 21 p.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2002. Simulation of growth and development of diverse legume species in APSIM. Aust. J. Agric. Res. 53, 429–446. http://dx.doi.org/10.1071/AR01106.

Sala, O.E., Parton, W.J., Joyce, L.A., Lauenroth, W.K., 1988. Primary production of the central grassland region of the United States. Ecology 69, 40–45. http://dx.doi.org/10.2307/1943158.

Sinclair, T.R., Muchow, R.C., 1999. Radiation use efficiency. Adv. Agron. 65, 215–265. http://dx.doi.org/10.1016/S0065-2113(08)60914-1.

Smith, R.G., Menalled, F.D., Robertson, G.P., 2007. Temporal yield variability under conventional and alternative management systems. Agron. J. 99, 1629–1634. http://dx.doi.org/10.2134/agronj2007.0096.

Teixeira, E.I., Brown, H.E., Sharp, J., Meenken, E.D., Ewert, F., 2015. Evaluating methods to simulate crop rotations for climate impact assessments-a case study on the Canterbury plains of New Zealand. Environ. Modell. Softw. 72, 304–313. http://dx.doi.org/10.1016/j.envsoft.2015.05.012.

Travis, R.L., Reed, R., 1983. The solar tracking pattern in a closed alfalfa canopy. Crop Sci. 23, 664–668. http://dx.doi.org/10.2135/cropsci1983.0011183X002300040015x.

Turner, N.C., Asseng, S., 2005. Productivity, sustainability, and rainfall-use efficiency in Australian rainfed Mediterranean agricultural systems. Crop Pasture Sci. 56, 1123–1136. http://dx.doi.org/10.1071/AR05076.

Turner, N.C., 2004. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. J. Exp. Bot. 55, 2413–2425. http://dx.doi.org/10.1093/jxb/erh154.

Van Opstal, N.V., Caviglia, O.P., Melchiori, R.J.M., 2011. Water and solar radiation productivity of double-crops in a humid temperate area. Aust. J. Crop Sci. 5, 1760–1766.

Verón, S.R., Oesterheld, M., Paruelo, J.M., 2005. Production as a function of resource availability: slopes and efficiencies are different. J. Veg. Sci. 16, 351–354. http://dx.doi.org/10.1658/1100-9233(2005)016[0351:PAAFOR]2.0.CO;2.

Wiegand, T., Snyman, H.A., Kellner, K., Paruelo, J.M., 2004. Do grasslands have a memory: modeling phytomass production of a semiarid South African grassland. Ecosystems 7, 243–258. http://dx.doi.org/10.1007/s10021-003-0235-8.