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# Efficiency and stability in subtropical beef cattle grazing systems in the northwest of Argentina

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ABSTRACT

The objective of this work was to evaluate the efficiency and stability of cow–calf, fattening and whole cycle beef cattle agro-ecosystems from the subtropical region of Argentina. For this purpose, an agro-ecosystem model consisting of a production and a management system was developed. Flexible management rules were incorporated. This simulation-based study compared potential trends of different agro-ecosystems under different animal body sizes and several management options traditionally applied in the region. The experiment aimed at estimating productive, energetic and economic efficiency and stability. The results showed that whole cycle and cow–calf systems were more stable but less productive than fattening systems. Within each agro-ecosystem, as body size increased, energetic and economic efficiency and stability decreased. Systems dynamics and multi-criteria approaches allowed recognizing tradeoffs among indicators, and main differences between agro-ecosystems. Further investigation is required to generalize these findings to other system structures, particularly when economic aspects are taken into account in decision making processes.

## 1. Introduction

Given the complexity of animal production systems in subtropical and semiarid regions, scientists are increasingly relying on the use of simulation models as decision aids (Diaz-Solis et al., 2006). These agro-ecosystems include a myriad of important variables including climate, soil, and vegetation, as well as current range productivity, stocking rate, and market conditions, all of which influence management decisions. In the sub-humid and semiarid rangelands of northwestern Argentina, characterized by high rainfall variability, producers operate cow–calf, fattening and whole production systems. An issue for agriculture in many variable environments may be whether the best adaptive strategy is to choose a more specialized system or a system with greater diversity (Browne et al., 2013). This choice determines the structure and therefore the behavior of the system (Morecroft, 2007; Sterman, 2000). The behavior of a system can be described by emergent properties like efficiency and stability (Feldkamp, 2004; Viglizzo and Roberto, 1998). The question for beef cattle systems of the northwest of Argentina is: which agro-ecosystem structure shows better behavior as measured through its efficiency and stability? A multi-criteria approach considering productive, biological and economic aspects is necessary to assess this complexity (Giampietro, 2004).

The environment has a strong influence on beef cattle efficiency and stability, although there is little consensus regarding the existence of optimal mature cattle body size for specific production environments. Cattle size, maturing rate and milk production are important parameters in beef cattle production (Pang et al., 1999). The existence of optimal body size for specific environments has been investigated by numerous authors (Dickerson, 1970; Echols, 2011; Johnson et al., 2010). Body size can be represented by the frame size as a set of size-age points that gradually change in a particular animal until reaching a plateau at maturity (Arango and Van Vleck, 2002). Frame size is directly correlated with weight at maturity, animal growth rate, feed intake, nutritional requirements, reproductive efficiency, age at puberty, birth weight, pre-weaning gain and weaning weight (Menchaca et al., 1996; Olson et al., 1982; Vargas et al., 1999). With highly variable and dynamic physical and economic environments, one may consider variability of cow size as an asset to cow–calf producers (Echols, 2011).

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Lack of consideration of the type of agro-ecosystem, the environment and the frame size effect could restrict the improvement in efficiency and stability of beef cattle agro-ecosystems in Subtropical regions.

Thus, the objective of this work was to evaluate the efficiency and stability of cow–calf, fattening and whole cycle beef cattle agro-ecosystem from the subtropical region of Argentina. For this purpose, a dynamic simulation model was used to compare potential trends in performance of the systems under different frame scores and several management options traditionally applied in the region.

## 2. Materials and methods

### 2.1. Study area

Beef cattle agro-ecosystems in the northwest of Argentina are highly varied, ranging from extensive pastoral systems dominated by smallholder producers and semi-subsistence production, to large-scale, commercially oriented industrial production systems. The rainfall regime varies in space and time, determining occasional extreme conditions of droughts and floods over wide areas. Annual precipitation varies from 300 to 1000 mm. Grazing systems based on tropical pastures is a distinctive feature in medium and high intensified systems in the northwest of Argentina. Main tropical grasses used are: *Chloris gayana, Panicum maximum* and *Cenchrus ciliaris* (Ricci, 2006). Mostly, beef cattle systems keep all animal categories on pastures. Hay, silages and grains (as concentrates), and, to a much lesser extent, industrial feeds or by-products are provided, particularly when pasture availability, quality, or both do not meet animal consumption needs or nutrient requirements (Arelovich et al., 2011). Braford and Brangus biotypes are extensively used to increase the productivity of cattle in subtropical areas. Most farms perform whole-cycle production, running the cow–calf operation and finishing the animals in the same area. Carrying capacity of these agro-ecosystems typically ranges from 0.3 to 2 AU/ha. The degree to which this general description fits into agro-ecosystems varies from farm to farm.

For this study a database from the Animal Research Institute of Semiarid Chaco (IIACS) which belongs to the National Institute of Agriculture Technology (INTA, Argentina), was used. The data set included information that referred to different agro-ecosystems (cow–calf, fattening and whole cycle), climatic records (1973–2012) and soil characteristics of the systems considered. Main information of these agro-ecosystems include animal body weight, animal growth rate, body condition score, forage growth rate, total forage growth, forage quality, stocking rate, forage management, herd management, inputs (i.e., feed concentrates) and main outputs. The information covers the Depressed Saline Plain of the Province of Tucumán (Argentina). The mean annual precipitation is 880 mm (concentrated from October to March) with an inter-annual coefficient of variation of 35%. Mean monthly rainfall and standard deviations are shown in Fig. 1. Mean annual temperature is 19 °C, ranging from 25 °C in January to 13 °C in July. The climate is subhumid with a well-defined dry winter season (April to October).

### 2.2. Model overview

The model developed is deterministic, so that its outputs are primarily the result of the initial farm conditions, weather inputs during the simulation sequence, and the farm management strategy (Romera et al., 2006). The only stochastic components in the model are weather, pregnancy length, aborts and deaths. It allows the simulation of the stages of breeding, stocking and fattening either independently or as an integrated process within a production system. The agro-ecosystem model consists of a production and a management system (Feldkamp, 2004). The first part comprehends biophysical processes, named pasture growth, soil–water availability, animal growth, animal reproduction and animal feed intake. The second part of the agro-ecosystem model includes processes regulated by human intervention, i.e., management model (Fig. 2). We adapted several preexisting submodels: forage (McCall and Bishop-Hurley, 2003); animal (Feldkamp, 2004); feed intake (Freer et al., 1997) and soil–water (Cros et al., 2003).

The management model uses environmental and system information to evaluate criteria regulating the flows and determining the occurrence of processes. Therefore, the management model acts as a link between the production system, the inputs and criteria given by the user into the agro-ecosystem model (Feldkamp, 2004). The model is driven by decision rules entered by the user, which allows the representation of many different kinds of management options that respond to changing farm conditions (Romera et al., 2004).

### 2.3. Simulation model

The modeling methodology used to develop the mathematical model was system dynamics (Morecroft, 2007; Sterman, 2000), and it was programmed using Powersim Studio 8® model development platform. Powersim Studio 8® is an object-oriented graphical programming language designed specifically for modeling dynamic systems (Costanza et al., 1998; Smith et al., 2005). It requires identifying the system's variables, named stocks, flows, auxiliaries and constants; and establishes the appropriate connections among them. Variables defined as indexed variables or arrays hold several values, and their dimension and structure are defined by the user introducing the range and/or the sub ranges of the array. The array feature allows representing individual objects with particular attributes,

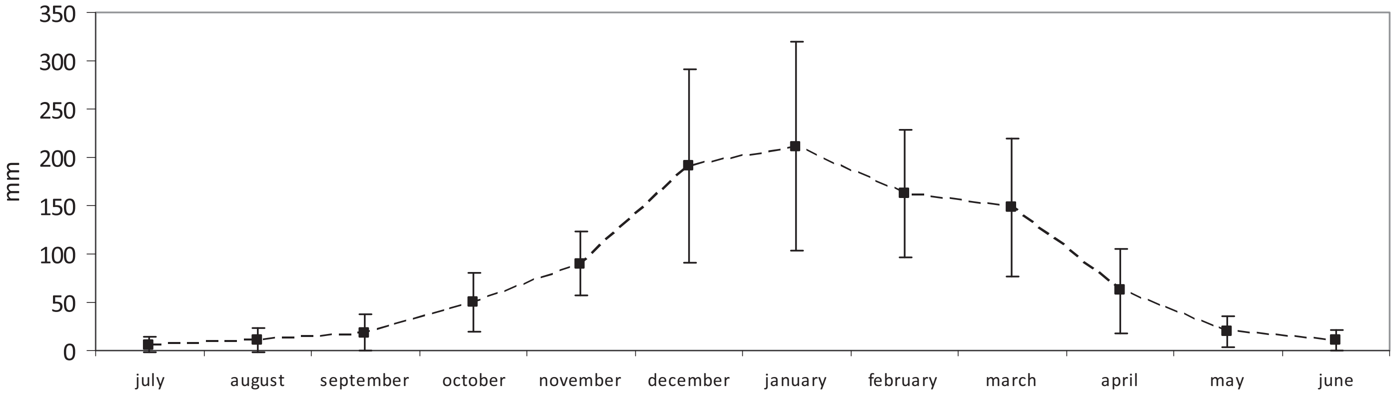

**Fig. 1.** Monthly mean precipitation (mm) for the series 1973–2012 in the Depressed Saline Plain of Tucumán Province (Argentina). Whiskers show ± standard deviation.

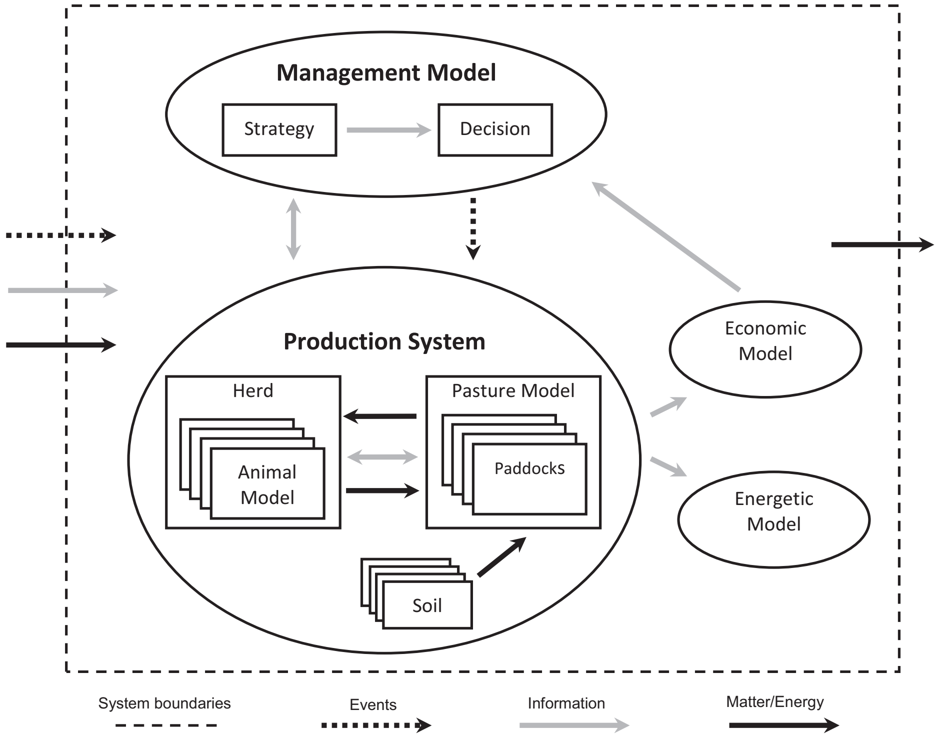

**Fig. 2.** Simplified representation of the agro-ecosystem model. (adapted from Martin et al., 2011)

grouped in several categories (i.e., herd categories and group of paddocks for each category). Thereby, each component (i.e., animal and paddock) retains its individuality throughout the whole model. The state of the model at a certain time is defined by the state of each component. At the next time interval, changes in the state of the system are calculated considering the interactions among the components (Feldkamp, 2004). The model requires establishing an integration interval (time step), a simulation length and the initial date, that for this work was 1 day, 100 years and the 1st of January, respectively.

### *2.4. Model inputs*

Once the structure of the model was laid out on the screen, farm characteristics, initial conditions, parameter values, decision rules, inputs and functional relationships were specified. Farm characteristics, initial conditions and main inputs are shown in Table 1.

The initial state of the farm defines the initial values of the attributes of the components of the farm (Romera et al., 2004, 2005) and the dynamic responses of the agro-ecosystem (Feldkamp, 2004). Before a simulation, parameter values and thresholds must be fixed; and decision rules must be specified. Main decisions related with discrete events include animal selection, paddock allocation, selling, culling, mating, weaning, category change, and supplementation.

Particular efforts were made to include in the model different animal body sizes. Adult body size was included in the model through the frame score value. The frame score is a linear measurement of adult potential size ranging usually between 1 and 9. Its value comes from an equation based on actual measurement of hip height and age (Guidelines for Uniform Beef Improvement Programs, 2010). Current frame score of cattle herds of the subtropical northwest region of Argentina was obtained through actual measurements (n = 1500) of males' and females' hip height in commercial farms (n = 7) and experimental stations (n = 1). Within each farm, current frame size (AFR) showed high variability (4.06 ± 0.75). Frame size variability was incorporated in the model through a normal distribution function, where each location in the array of animals carries a value frame size, so each individual of the herd has a specific body size. This would impact directly over the body weight at maturity, feed intake, age and weight at puberty and first mating, nutritional requirements (especially maintenance requirements), body growth rate, birth weight, potential milk production, pre-weaning growth rate, age and body weight at slaughter. In this work four frame sizes were evaluated: 3 (**FR3**), 4 (**FR4**), 5 (**FR5**) and current (**AFR**).

**Table 1**
Farm characteristics, initial conditions and main inputs required to use the model.

| | |
|---|---|
| Farm characteristics and initial conditions | Production system: cow–calf, fattening or whole cycle<br>Total area of the farm<br>Paddocks: number, size and whether these are separated into management blocks (i.e., assign a group of paddocks for a certain category: paddocks 1 to 5 for cows, 6 to 8 for heifers). For each paddock the user can select a soil type.<br>Initial herbage stock within each paddock<br>Total number of animals<br>Body size at maturity (frame size)<br>Target stocking rate<br>Initial herd structure. Defined as proportion of each category |
| Inputs | Weather: Mean, minimum and maximum temperature (°C); global radiation (MJ/m$^2$/day); Rain (mm/day)<br>Prices ($). The price of the animals was determined by the weight and the price per kilogram, which depends on the selling category. For each selling category, an annual fixed price was selected. Also requires input prices.<br>Energy inputs (Gj): Fossil energy consumed for obtaining concentrates and seeds, animal transportation and by agricultural activities (i.e., ploughing, harrowing, seeding, spraying, harvesting and water pumping).<br>Imported feed: concentrates (i.e., maize, sorghum)<br>Purchasing animals (only for fattening systems) |

**Table 2**
Efficiency, stability and corresponding energetic, productive and economic indicators.

| Properties | | Indicators | Units |
|---|---|---|---|
| Efficiency | Energetic | Gross energy output per unit of forage energy consumed | Mj produced·Mj forage consumed$^{-1}$ |
| | | Fossil energy consumed | Gj·ha$^{-1}$·year$^{-1}$ |
| | | Energy produced | Gj·ha$^{-1}$·year$^{-1}$ |
| | | Fossil energy use efficiency | GJ produced·GJ consumed$^{-1}$ |
| | Productive | Empty body weight produced or sold | kg EBW produced·ha$^{-1}$·year$^{-1}$<br>kg EBW sold·ha$^{-1}$·year$^{-1}$ |
| | Economic | Gross margin | $\$\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ |
| Stability | Energetic | As the standard deviation and the coefficient of variation of the efficiency indicators | |
| | Productive | | |
| | Economic | | |

### 2.5. Emergent properties and model outputs as selected indicators

The efficiency and stability of the agro-ecosystems were evaluated through energetic, productive and economic indicators (Table 2).

The analysis of energy fluxes involved estimates of inputs in the form of fossil energy consumed and outputs in the form of agricultural products (Kraatz, 2012; Viglizzo et al., 2003, 2010).

Gross margin was calculated considering variable costs (i.e., veterinary inputs, supplements, labor costs, forage amortization and trading costs) and gross cash income from animals and hay sold. In addition, dynamics of the stocking rate and herd were considered.

### 2.6. Management simulation

The dynamics of the whole farm is dominated by rules, consisting of conditions and actions, which interact with the biophysical components and the environment to produce a pattern of production (Martin et al., 2012; Shaffer and Brodahl, 1998). The conditions may depend on the physical attributes of the animals, herd or paddock, the environmental situation, the calendar date or on decision variables. Every condition consists of at least one comparison of an attribute of any component of the system against a constant or another attribute. The rules consider long term goals (i.e., target stocking rate), as well as tactical and operational actions to manage immediate problems or opportunities (i.e., selling cows, heifers or steers in response to a severe drought). The model includes a set of rules under an “if conditions true then action” format which defines the nature of a decision to be made when specific conditions are encountered. A general simplified algorithm determining weaning strategy is presented below as an example (Fig. 3).

This algorithm could be applied for the entire herd by introducing mean values i.e., mean body condition score (BCS), or taking into account individual BCS, allowing a stepwise weaning. Thresholds are mobile, depending on the conditions encountered, i.e., forage threshold is not the same for each season considered. The model is robust in cases where the sequencing of events is obligatory (i.e., weaning after calving). But, when the strategy requires a specific sequence of actions, then it is necessary to enter rules that trigger the actions in the desired timing (Romera et al., 2004). Conflicts require establishing priorities among rules, i.e., two or more paddocks available for haymaking and only one could be clipped each month.

### 2.7. Model calibration and evaluation

Calibration and evaluation are two important steps prior to the application of a simulation model (Yang et al., 2014).

#### 2.7.1. Pasture growth model calibration and evaluation

McCall and Bishop-Hurley (2003) pasture growth model, modified by Romera et al. (2009), was used. It is a generalized climate-driven model that describes dry matter production and green-dead tissue flow dynamics for grazed pastures. Certain components

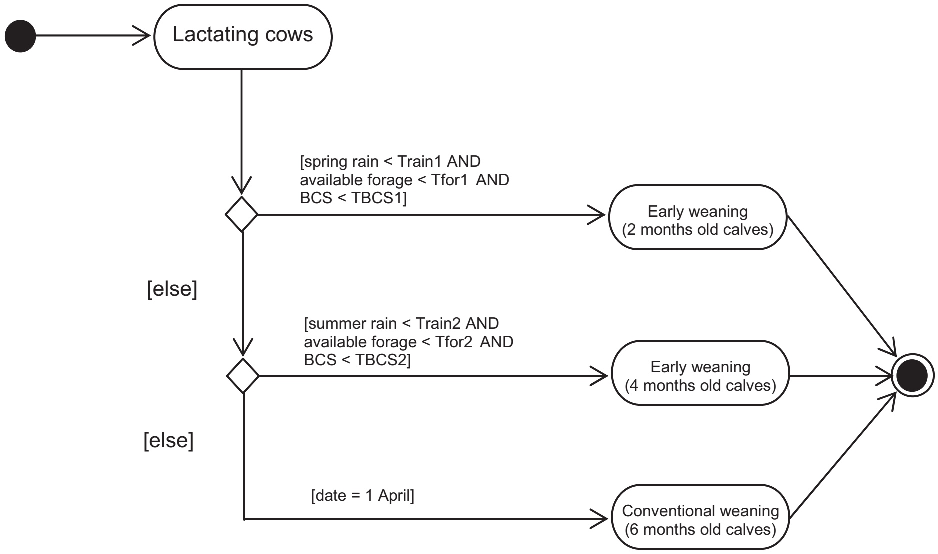

**Fig. 3.** Unified Modeling Language Activity Diagram showing the weaning strategy. Thresholds (T): Train1: spring rain (September to November) 40% below of historical average; Train2: summer rain (December to January) 40% below of the historical average; Tfor1: available forage below 800 kg DM·ha$^{-1}$; Tfor2: available forage below 500 kg DM·ha$^{-1}$; TBCS1 and 2 with a default value of 3.

in the model rely on empirical parameters, requiring site-specific calibration (Romera et al., 2009). Range of parameter values for tropical pastures, and specifically for *C. gayana* pasture were taken from literature review (Agnusdei et al., 2009; Avila et al., 2012; Martínez Calsina et al., 2012; Moser et al., 2004). Calibration was performed by altering the values of parameters in order to obtain the best fit between the simulate outputs and measurements made in real systems (Ahuja and Ma, 2002; Carlson et al., 1993).

Calibration was done by comparing dry matter accumulation between defoliation events with field data. Root mean square error (RMSE) was used. The pasture model was calibrated and evaluated against data from experiments carried out in the IIACS, with *C. gayana*. The experiments were conducted during ten years (2001–2010) involving sequential grazing periods. For each paddock ($n = 24$), biomass was harvested three to four times per year between November and April. Amount of harvested biomass was determined by measuring available forage immediately before and after grazing periods. Rotational grazing was employed wherein paddocks were grazed for 4–7 days. We used five years of the dataset to calibrate the model, and another five years to evaluate the model. Weather data for the corresponding periods was collected at IIACS and used for the simulation. Also soil characteristics were included for the calibration. For the evaluation we also included three experiments conducted by Ricci (2006) in three different sites.

Once the model was calibrated, evaluation was performed. Deviation statistic RMSE and t-test were selected so that a representative statistical conclusion could be drawn from them (Yang et al., 2014). The results were consistent with the model purpose, indicating that it was useful to describe pasture production and variation in production between seasons, as well as within season variation caused by climatic and grazing effects.

### 2.7.2. Feed intake model calibration and evaluation

The model adopted does not attempt to represent underlying biological processes, but to accurately estimate feed consumption from some pasture attributes and animal characteristics (Feldkamp, 2004). The dataset mentioned in section 2.7.1 was also used to calibrate and evaluate the feed intake submodel. Additionally, this dataset contains information related with pasture quality and animals' characteristics (categories, sex, body size and body weight). During winter (May to October), deferred tropical grasses were used to calibrate and evaluate the model (Imaz et al., 2014). In order to have a better assessment of the accuracy of the adopted model we compared the results with those obtained with the National Research Council (NRC) (1996).

Once the model was calibrated, evaluation was performed. Deviation statistic RMSE was selected. In the evaluation, the adopted model produced results more accurate than National Research Council (NRC) (1996). The results were consistent with the model purpose.

### 2.7.3. Animal growth model calibration and evaluation

The animal growth model had been already calibrated and evaluated by Feldkamp (2004) and Nasca et al. (2012). No further efforts were done as the results found were consistent with the model purpose.

### 2.7.4. Whole model evaluation

Many authors suggest that it is not possible to evaluate complex models with empirical tests, and proposed subjective, rational or face evaluations (Andrieu et al., 2007; Harrison, 1990; Rykiel, 1996; Vayssières et al., 2009). Subjective evaluation consists of presenting to experts results of simulations from cases similar to their own studies and asking them whether the behavior of the model appears to be realistic or not. This test suggests whether the model logic and input–output relationships appear reasonable given the model's purpose (Rykiel, 1996). For this work three experts were consulted for the whole model evaluation. The general structure of the model, two scenarios and the simulation results were subsequently presented to the experts involved. They found that the simulated results were consistent and realistic given the scenarios considered and the purpose. Suggestions were made, discussed and finally incorporated, making this validation an integral part of the process of development of the model (Andrieu et al., 2007).

## 2.8. Sensitivity analysis to body sizes and weaning strategies

Rainfall variability and soil water availability are strong driving factors for the agro-ecosystems of the northwest of Argentina. Due to climatic variability, a major decision is the determination of stocking rate for each pasture, since this affects the balance between animal population and forage availability. Forage production, which determines animal production, is controlled by climatic factors. Management strategies for dealing with drought might include increasing or decreasing stocking rate based on the current condition of the pasture, season of the year, and the direction and rate of change in animal body condition (Diaz-Solís et al., 2009). Managers also might influence body condition by weaning calves early and/or shifting the breeding season such that the period in which nutrient requirements of animals are highest coincides with the period of highest forage quantity and quality. Although the coming drought is unpredictable, we can reduce its negative effects by an appropriate selection of animal's body size, and timely adjustments of animal stocking rates (Diaz-Solís et al., 2009). A sensitivity analysis to identify the impact of different body sizes and different weaning strategies on the stocking rate behavior was performed for cow–calf and whole cycle systems. We evaluated three management strategies (MST) over 65 years of simulation, using actual climatic series from the original 40 years data from the IIACS (1973 to 2012), repeated over time to obtain a series of 100 years. Four body sizes were used for each strategy, named FR3, FR4, FR5 and AFR. The target stocking rate was fixed in 350 kg $\text{EBW}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$. Management strategies implemented were: MST1 with no adjustments to stocking rate and conventional weaning (6 month old calves); MST2 with no adjustments to stocking rate and flexible weaning, and MST3 with stocking rate adjustment rules and flexible weaning. Flexible weaning is shown in Fig. 3. If early weaning was performed (MST3) adjustments to stocking rate involved selling all the steers, 60% of the yearling heifers and 20% of weaned cows.

## 2.9. Model assumptions and main decisions rules

For the comparison among agro-ecosystems (whole cycle, cow–calf and fattening) and animal body sizes, certain assumptions and decision rules were established.

A farm of 500 ha was defined for all treatments in this study. The stocking rate (SR) was adjusted for a similar body weight mass per unit of area. The management model defined a variable called target stocking rate (TSR), which represents the objective value of empty body weight (EBW) per unit of area. Assumed TSR of 350 kg $\text{EBW}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ was based on values obtained from many herds of the northwest region of Argentina (García Posse et al., 2010).

Heifers were first mated at 25 to 27 months of age. The breeding season ran for 90 days from December to February. Replacement decisions were dynamically produced in order to achieve TSR. Cows and heifers were culled if they were not pregnant. Decision rules did not take into account animal purchases. Management strategy implemented was MST3.

Supplementation was exclusively used for replacement heifers and fattening categories (i.e., steers, heifers and culling cows). Supplementation level was regulated to cover a daily feed intake of 9.6

Mj ME·kgDM$^{-1}$ up to a maximum supplement intake of 1% of EBW (DM basis).

Fattening (F) system includes purchasing animals once a year (April), to be comparable to whole cycle (WC) systems. Generally, criteria for selling steers and heifers were the same for WC and F. The fattening model includes a decision rule accounting for the economic result of the operation. When total costs are higher than annual gross income, the model sells animals in order to breakeven, regardless of whether they are finished or not. Prices adopted for those animals were less than prices obtained for animals that are sold timely. The fattening model was oriented toward beef cattle grazing systems that finish steers or heifers for a period that runs for 365 to 1095 days. Grain supplementation during summer was used when EBW and BCS were above certain threshold varying with age and frame size, mimicking the typical management procedures of the farmers in the region.

Harvesting was allowed within 1 December to 15 February, depending on forage availability. The model assumes that conserved forage cannot be fed to animals, but sold. Consequently, a price was assigned to conserved forage.

Twenty artificial sets of 100 years of weather data were generated by randomly selecting years from the original 40 years data from the IIACS (Romera et al., 2004; Woodward et al., 2008). Means and standard deviation for different performance indicators were statistically compared by considering each of the 20 simulations of 100 years as an independent replicate (Romera et al., 2005). In order to reduce the impact of initial values, the model was run 100 years and all analyses were done with the last 65 years.

Model outputs were statistically analyzed with R. The study was arranged statistically according to the following model:

$$y_{ijk} = \mu + FR_i + S_j + (FR\ S)_{ij} + R_k + e_{ijk}$$

i = 3, 4, 5 and actual frame sizej = cow–calf, fattening and whole cycle systemsk = 1,2…20where $y_{ijk}$ is the *ijk*th observation; $\mu$ the general mean; $FR_i$ = the effect of the *i*th frame size; $S_j$ = the effect of the *j*th agro-ecosystem; (FR S)*ij* = the effect of the interaction between the *i*th frame size and the *j*th agro-ecosystem; $R_k$ = the effect of the *k*th replication (run of 100 years) and $e_{ijk}$ the error term.

Normality and homoscedasticity of the error term were tested. Means were compared by Tukey test, and significant differences were declared when $P < 0.05$.

## 3. Results and discussion

### 3.1. Sensitivity of results

When considering each frame size, simulated stocking rate tended to increase as MST2 and MST3 were implemented (Fig. 4).

Particularly, larger frame sizes (FR5 and AFR) showed a poorer performance in MST1, pointing out that early weaning and strategic selling were two positive interventions, although they did not reach the target stocking rate (350 kg EBW·ha$^{-1}$·year$^{-1}$).

Fig. 5 showed the relative improvement of mean stocking rate for different agro-ecosystems and body sizes when MST2 and MST3 were implemented.

Flexible weaning (MST2) allowed increasing the stocking rate for all frame sizes compared with MST1 (Fig. 5). Differences between average simulated stocking rates were up to 18% between MST1 and MST2 in FR5 and AFR. When flexible weaning and selling strategies were implemented differences between averages simulated stocking rate were above 55% for FR5 and AFR.

Analyzing the results of MST3 we found that within each agro-ecosystem (WC and CC), FR5 and AFR reported a large number of open cows after the breeding season although the stocking rate was diminishing. Moreover, the number of open cows for FR5 and AFR was more variable than FR3 and FR4. On the one hand, results in this work showed that when forage availability was not a limiting factor, a high percentage of cows conceived early during the breeding season. On the other hand, low forage availability delayed the conception, pushing most cows out from the breeding period, being this particularly important for FR5 and AFR.

For FR5 and AFR the strategies implemented were not enough to achieve the TSR, and perhaps, it would be important to evaluate and incorporate other technologies which allow enhancing forage availability, like perennial forage shrubs, maize, sorghum or grass silage.

### 3.2. Stocking rate results

It is widely accepted that stocking rate is a significant component of grazing management from the point of view of vegetation, livestock, wildlife, and economic return (Riechers et al., 1989). In this regard, we observed that different frame scores achieved and maintained diverse annual SR (Fig. 6).

For WC and CC, FR3 and FR4 performed better than FR5 and AFR. In both agro-ecosystems, both FR3 and FR4 were close to TSR. Note that AFR, which is the current frame size of most farms in the region, did not achieve in any case the TSR, and its performance was similar to FR5 and lower than FR3 and FR4 for WC and CC. Notably, researchers and advisors use FR4 as an appropriate frame score value to calculate and design their work, mostly related with cattle nutrition and herd management (Orellana et al., 2009), not taking into account that the variability might be an important source of error in their projects. Selection of a target stocking rate and an animal body size are strategic decisions within a farm, which implies in many cases that they are difficult to implement (Chapman et al., 2013).

In fattening systems, all frame sizes achieved TSR. The dynamic of stocking rate in fattening systems (data not shown) was similar for different body sizes. Unexpectedly, higher stocking rates were coincident in several cases with drier than average years, with lower forage availability, with a consequent high retention of heavy animals. Supplement feeding in those years was not sufficient to support daily live weight gains to finish the animals. This generates a counterintuitive thinking, because increasing the level of supplementation might allow decreasing the stocking rate through higher daily live weight gain and shorter finishing periods.

Comparing each frame size among different agro-ecosystems (i.e., WC-FR3 vs CC-FR3 vs F-FR3), WC and CC were more stable than F (lower coefficient of variation).

### 3.3. Energy indicators results

From the viewpoint of animal production, it is of interest to establish the efficiency of use of the forage produced and consumed (Feldkamp, 2004). These ratios are usually expressed in terms of energy, in order to make them comparable among systems using different feeds and/or products of different energetic densities.

Results of the energetic efficiency, measured as gross energy output per unit of the forage energy consumed, are shown in Fig. 7.

Fattening systems were more efficient than WC and CC for all frame sizes considered (Fig. 7). This is mainly related with the incorporation of supplemental feed. Likewise, supplementation explained differences between WC-FR3 and CC-FR3; and WC-FR4 and CC-FR4. Whole cycle and cow–calf systems associated with smaller frame sizes (FR3 and FR4) were more efficient than larger ones (FR5 and AFR).

Feldkamp (2004) found that when efficiency was expressed in terms of gross energy output per unit of forage energy consumed, efficiency decreases as stocking rate increases. This is expected because the better fed herd in the low stocking rate system has

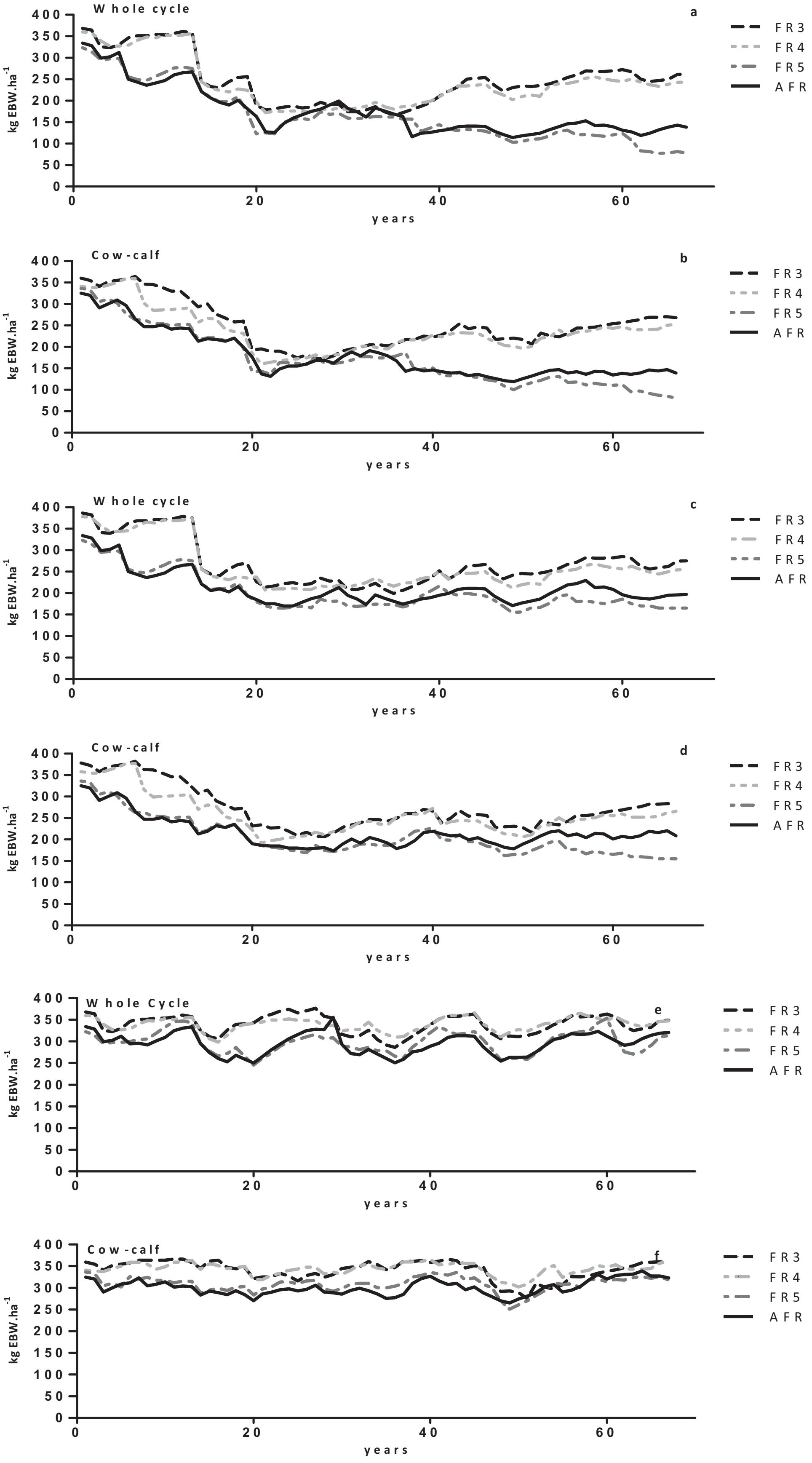

**Fig. 4.** Dynamic evolution of the stocking rate for whole cycle (WC) and cow–calf (CC) systems, with different frame sizes and management strategies (MST), over the 65 years of simulation: a: MST1 WC; b: MST1 CC; c: MST2 WC; d: MST2 CC; e: MST3 WC; f: MST3 CC.

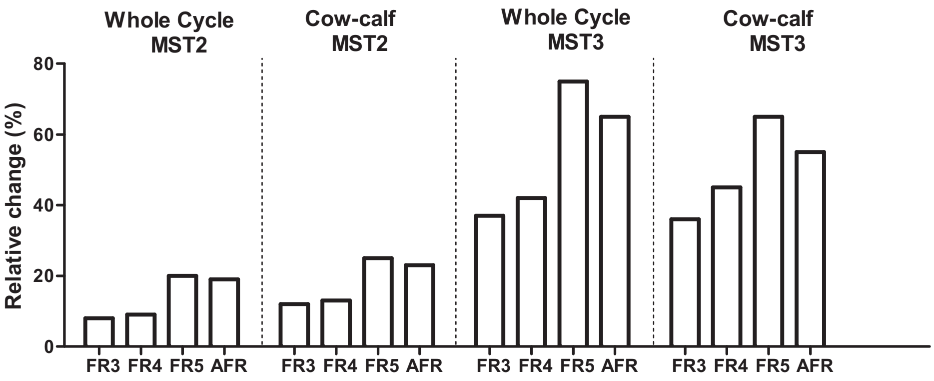

**Fig. 5.** Effects of different management strategies shown as relative change in mean values compared with MST1, for four body sizes considered in whole cycle and cow–calf systems.

higher productivity than herds in lower body condition of systems with higher stocking rates. In contrast, when lower stocking rates are due to the instability of the system, efficiency decrease as the average stocking rate decrease. These findings suggest that identifying the reason behind the average stocking rates in a given farm is important to be able to relate it to the energetic efficiency of the agro-ecosystem.

### 3.3.1. *Fossil energy use and fossil energy use efficiency*

Like any other activity involving nature, agriculture affects and is affected by the environment (Viglizzo et al., 2003). In agriculture, the efficient use of energy is one of the priorities for sustainability (Kraatz, 2012). Energy-efficient agricultural processes permit fossil resources preservation, a decrease in air pollution and financial savings.

Fig. 8 shows fossil energy consumed (Gj·ha$^{-1}$·year$^{-1}$), energy produced (Gj·ha$^{-1}$·year$^{-1}$) and fossil energy use efficiency (GJ produced·GJ consumed$^{-1}$) for different treatments.

The use of fossil energy highly correlates with intensification of agriculture (Cleveland, 1995). The results of the present study indicated that the energy consumed increased in fattening systems for all frame sizes compared with WC and CC (Fig. 8a). Animal transportation from cow–calf systems and to slaughter plants; and feedstuffs brought into the cattle systems had an important influence in fossil energy consumption for fattening systems. The variation of the feeding strategy by reducing the proportion of pasture in the

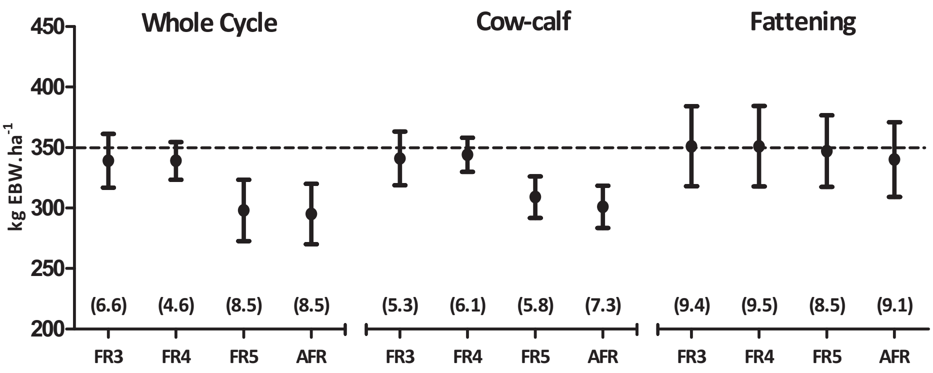

**Fig. 6.** Mean annual stocking rate (n = 20) (kg EBW·ha$^{-1}$·year$^{-1}$) for different frame sizes (FR) and different agro-ecosystems. Vertical lines indicate standard deviation. Coefficients of variation (%) are in brackets. Dotted line represents the target stocking rate (350 kg EBW·ha$^{-1}$·year$^{-1}$).

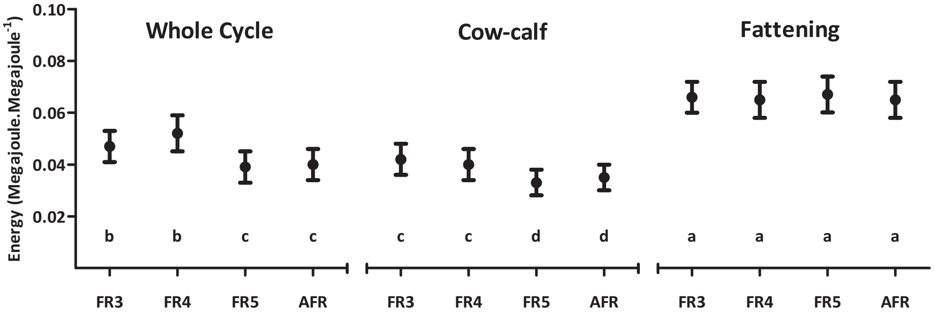

**Fig. 7.** Energetic efficiency expressed as gross energy output per unit of the forage consumed for different frame sizes (FR) and different agro-ecosystems. Dots represent the average of 20 replicates and whiskers represent the standard deviation. Different letters indicate a difference among treatments with a probability of $P < 0.05$.

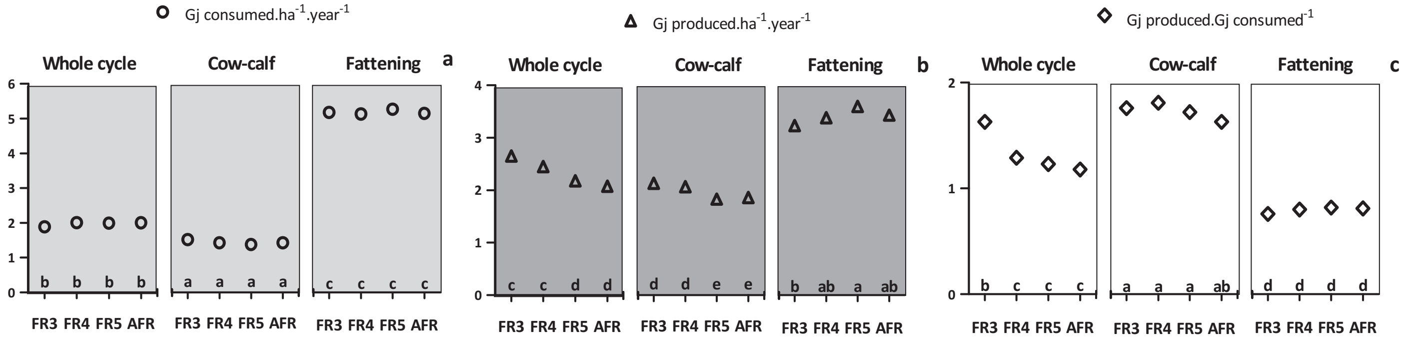

**Fig. 8.** Efficiency expressed as fossil energy consumed (Gj·ha$^{-1}$·year$^{-1}$) (a), energy produced (Gj·ha$^{-1}$·year$^{-1}$) (b), and energy use efficiency (Gj produced·Gj consumed$^{-1}$) (c), for different frame sizes and cattle systems. Different letters indicate a difference between treatments with a probability of $P < 0.05$.

diets, leads to an increase of energy intensity (Kraatz, 2012). In our work, fattening systems (F) consumed 2.6 times more fossil energy than whole cycle systems. Veysset et al. (2010) working in grazing cattle systems in the depressed-area of the Massif Central (France) found values of fossil energy consumed ranging from 22000 to 28000 Mj. 1000 kg live weight produced$^{-1}$·year$^{-1}$. Energy consumption for whole cycle and cow–calf systems of the northwest of Argentina was lower than for the French systems, ranging from 9900 to 13,300 for WC, and 9650–10,800 for CC. Fattening systems showed similar values to Veysset et al. (2010), ranging from 20,600 to 22,800 Mj. 1000 kg live weight produced$^{-1}$·year$^{-1}$. The information given by this indicator is not absolute but based on a reference, which corresponds to a sustainable energy use, or at least, to more sustainable uses (Pervanchon et al., 2002).

Increasing energy consumed resulted in increased energy production (Fig. 8b). In relative terms, this relationship was not proportional, so the efficiency of energy use (GJ produced·GJ consumed$^{-1}$) was poorer for fattening systems, compared to WC and CC (Fig. 8c). Frank (2007) worked in mixed grain crop–cattle production systems and found that annual crops increased fossil energy consumption and energy production, enhancing the efficiency use.

Results obtained in this work showed that cow–calf systems such as those chosen for this study were less productive, had less fossil energy consumption, and were more efficient than WC and F (Fig. 8a, b and c).

Efficiency in a productive process should be measured in relation to the limiting input (Gingins and Viglizzo, 1981). This places the whole cycle and cow–calf grazing cattle systems in an advantageous position considering fossil energy as a restriction. Although fattening systems had more energy consumption and less efficiency than WC and CC, when we compared these systems with feedlots, we observed that energy consumption in grazing systems is 9 times lower than that of intensive fattening systems. The environmental impacts of an expanding beef herd based on higher external inputs in the northwest of Argentina are not well documented. Bioeconomic pressure is the main driver of intensification of agricultural production at the farming system level (Giampietro, 2004). It seems necessary to develop strategies that allow increasing quantities of commercially edible products per unit of fossil energy, under grazing cattle systems. Whole cycle systems showed some advantages over cow–calf and fattening systems, as they offer a marketable product for direct consumption. Moreover, whole cycle systems were more stable than cow–calf and fattening system. WC-FR3 was the most stable agro-ecosystem (CV 3.6%). Fattening systems were more variable than CC and WC, without significant differences among frame sizes.

### 3.4. Productive results

Different strategies (agro-ecosystems – frame size) generated different results in terms of empty body weight produced and sold. The efficiency and stability expressed as the mean annual empty body weight sold and its standard deviation are shown in Fig. 9.

Productivity per unit of area differed across frame sizes and cattle agro-ecosystems (Fig. 9). The highest productivity was achieved by F-FR5 and F-AFR, while the lowest values were for CC-FR5 and CC-AFR. Fattening systems were more productive than WC and CC for all frame sizes considered, and whole cycle systems were superior to cow–calf agro-ecosystems. WC-FR3 and WC-FR4 were 35% more productive than CC-FR3 and CC-FR4. Fattening systems showed that as animal body size increased, productivity increased.

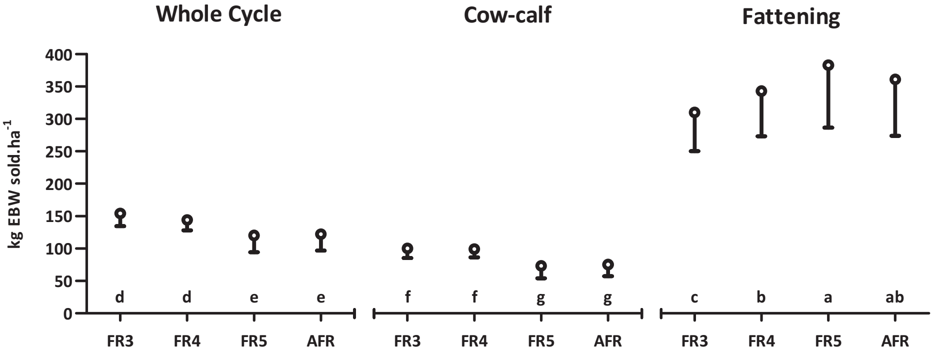

**Fig. 9.** Mean empty body weight sold ($n = 20$) (kg EBW·ha$^{-1}$·year$^{-1}$) for different frame sizes (FR) and different agro-ecosystems: whole cycle system (WC); cow–calf (CC); fattening (F). Whiskers indicate standard deviation. Different letters indicate a difference between treatments with a probability of $P < 0.05$.

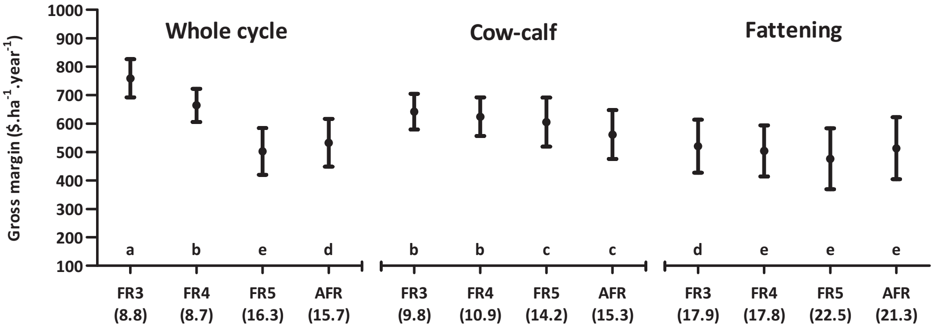

**Fig. 10.** Mean annual gross margin ($·ha$^{-1}$·year$^{-1}$). Values represent the mean values (n = 20). Vertical lines indicate standard deviation. Coefficient of variation (%) values are in brackets. Different letters indicate a difference between treatments with a probability of P < 0.05.

It is interesting to note that in the present study, AFR in cow–calf and whole cycle systems had lower values of efficiency, and that higher productivities were associated with lower frames. Cattle vary widely in body size, but optimal size depends on the agro-ecosystem (Arango and Van Vleck, 2002). Higher productivity could be achieved with smaller animals, as they were 20% more efficient than the large ones (Rutherford et al., 2003). Cow–calf and whole cycle systems performed better with lower frame sizes, and fattening systems had better productivity with higher frame sizes. The question would be: which frame size should be used in subtropical regions? Although fattening farmers could be interested in larger frame scores, if the agro-ecosystem structure remains unchanged, increasing the animal body size could be a risky option for the whole system.

Finding agro-ecosystems that increase efficiency and stability will likely require adoption of novel technologies and modified farming systems (Monjardino et al., 2010). Farmers are good at adapting to change, responding to year-to-year fluctuations in rainfall and prices by varying operational strategies, or adopting new technologies (Asseng and Pannell, 2013). Technologies like perennial forage shrubs can play a substantial role in the region, increasing productivity (Radrizzani and Nasca, 2014), enhancing economic returns and helping address environmental challenges (Monjardino et al., 2010), by reducing the amount of external inputs.

WC and CC associated with lower frame sizes (3 and 4) had more stability than other systems. Higher efficiency of fattening systems was associated with less stability, with coefficient of variation ranging from 11 to 14% for F-FR3 and F-FR5 respectively. The comparison between frame size and agro-ecosystems showed that higher frame sizes were more variable for all herd categories considered, with the exception of calves.

Overall, WC-FR3 and WC-FR4 seem to show a better combination between efficiency and stability, although they were not superior in either property compared with the other treatments. Increasing the efficiency (kg EBW·ha$^{-1}$·year$^{-1}$) of grazing systems in variable environments would require understanding the variability of productivity (Bell et al., 2008). Sources of variability and potential trends should be studied to design useful decision rules for managing agro-ecosystems.

In agro-ecosystems that rely on rainfall as the sole source of moisture for crop or pasture growth, seasonal rainfall variability is mirrored in highly variable production levels (Browne et al., 2013; Cooper et al., 2008). Irisarri et al. (2014) showed that the inter-annual variability of net secondary production was not related to the inter-annual variability of annual precipitation. Input variability is not simply related with output variability. Time delays of temporal models (Diaz-Solís et al., 2009; Diaz-Solis et al., 2003; Sala, 2001) and factors related to soil water availability (Bell et al., 2013; Chapman et al., 2013), may explain this lack of relation. The interaction between soil and environment (weather) within farms should be considered when predicting individual paddock pasture growth and when devising paddock-scale management of inputs and animals (Clark et al., 2010).

### 3.5. *Economic results*

Annual profit as measured by gross margin (**GM**) in $·ha$^{-1}$·year$^{-1}$, is shown in Fig. 10. Mean annual gross margin ranged between 476 and 759 $·ha$^{-1}$·year$^{-1}$ for F-FR5 and WC-FR3 respectively.

WC-FR3, WC-FR4, CC-FR3 and CC-FR4 achieved higher values of gross margin than the other treatments. Collectively, for WC and CC systems, as frame size increased, gross margin decreased. Fattening systems were unaltered by frame size, whereas whole cycle systems linked with FR5 and AFR showed steeper falls compared with smaller frame sizes.

From the stability viewpoint, WC-FR3, WC-FR4, CC-FR3 and CC-FR4 showed lower values of coefficient of variation, indicating less variability (Fig. 10). Fattening systems were more variable for all frame sizes than the other agro-ecosystems, which may be mainly related with supplementation and selling strategies. Thus the model established thresholds for selling related to age, EBW and BCS and set limits to grain supplementation when forage availability was restrictive to support moderate to high daily gains. These generated years with very low amount of animals sold, and years with a high amount of kg sold. Supplementation is traditionally viewed as a factor that contributes to enhancing the stability of cattle systems; however, decision rules used in the current model did not allow so. Volatility of price of grains determines that northwest Argentine beef farmers do not use supplements beyond certain limits (i.e., 1% of EBW in DM), thus the practice is perceived as risky (Orellana et al., 2009). Risk perception and uncertainty about the future are major factors limiting the adoption of new technologies in agriculture (Marra et al., 2003).

Risk management strategies such as selling livestock in droughts to reduce feed costs and judicious purchase of additional stock in better seasons would reduce debt and enhance gains (Salmon and Donnelly, 2007). The risk-efficient frontier can be used as a decision tool by the producer to select where to operate depending on how much profit he/she wishes to obtain and how much risk he/she is willing to take (Cacho et al., 1999). Each point on the frontier represents a different strategy. Fig. 11 shows that using gross margin as criterion, WC-FR3 and WC-FR4 are preferred to other options, because they achieve higher mean gross margin with similar or lower risk.

Current frame size (AFR), for WC, CC and F, is below the risk-efficient frontier and far away from the efficient line.

Both EBW and GM were affected by frame size and agro-ecosystem (Figs. 9 and 10). Economic impacts often do not follow simply and directly the biological impacts (Pannell, 1999). We found

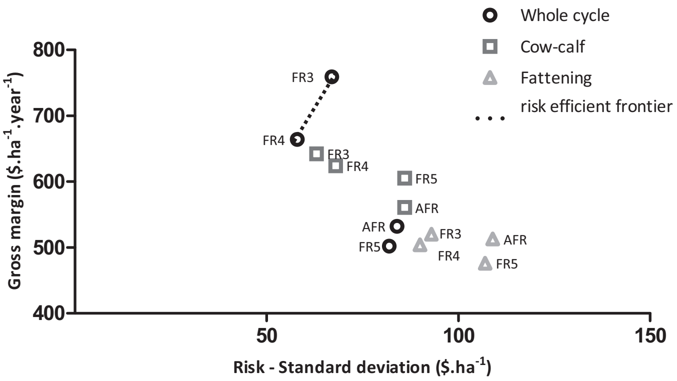

**Fig. 11.** Risk-efficient frontier graphic for gross margin. Values are calculated from the last 65 years of each model run.

that the highest productive efficiencies (kg EBW sold·ha$^{-1}$·year$^{-1}$) did not correspond in all cases with the highest profitability efficiencies, measured as GM ($·ha$^{-1}$·year$^{-1}$). This trade off was mainly related with different production costs, and the different structure of animal categories that were sold.

The amount of supplementary feed affected the profitability of beef cattle enterprises, and resulted in higher variability of costs (Browne et al., 2013; Ruiz et al., 2000). Supplementation costs represented an important part of the overall costs of production in whole cycle (50–62%) and fattening systems (60–67%). Whole cycle and fattening systems use a large proportion of concentrates during dry years, and this was not compensated with a proportional increase in productivity in WR-FR5, WC-AFR and all frame sizes of fattening systems.

Browne et al. (2013) pointed out that relative low profitability of beef cattle grazing enterprises is unlikely to change unless farmers can improve their pastures and feed efficiency, reducing supplementary feed costs and increasing the stocking rate of these enterprises. Reducing costs through reducing supplementary feeds, probably, would trigger in the short term an increase in the amount of animals per hectare, because of a developmental delay in growing categories. In the medium term, the stocking rate tends to decrease due to the poor reproductive performance of the cows, and the agro-ecosystems tend to be less efficient. Thus in the medium term, reducing supplementary feed could result in more unstable agro-ecosystems. This is particularly important when higher frame sizes are used.

The dynamic evaluation of the structure allows capturing the variability in the herd structure, and as a consequence, in the categories sold. Marketing decisions, such as culling cows from the herd, play an important role in determining profitability on a farm (Turner et al., 2013). Increasing cow sales in certain years, because of drought, had a major impact in those years, but in general the overall consequence was more variable agro-ecosystems. Increments in the amount of kg sold did not necessarily result in increased gross incomes, due to differences in prices and production costs. It is important to point out that the model did not consider that reducing cow numbers during droughts generally coincides with reduced market prices and that restocking after normal rains coincides with higher market prices (Diaz-Solís et al., 2009). This consideration could be important especially for FR5 and AFR.

## 4. Conclusions

Efficiency and stability issues need to be discussed in the context of a specific agro-ecosystem, which requires careful analysis of the environment and objectives of that production system. Components like animal body size or rainfall variability do not fully explain a system's behavior, which would differ depending on the system structure studied (i.e., cow–calf, fattening, whole cycle). The use of flexible management rules allowed the system to react to changing biological circumstances. Further efforts must be done to incorporate economic factors as criterions for decision making.

Our results support the idea that smaller animal body sizes could be more adequate to produce beef in whole cycle and cow–calf agro-ecosystems of the subtropical region of Argentina. Furthermore, systems dynamics and multi-criteria approaches allowed recognizing tradeoffs among indicators, and main differences between agro-ecosystems.

Findings of this paper indicate that agricultural research should avoid promoting a particular agro-ecosystem or an animal body size as a one-size-fits-all solution to efficiency and stability. Recognizing heterogeneity of farming circumstances and identifying differences in agro-ecosystems may lead enhancing beef cattle production of the northwest of Argentina.

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