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Research paper

Energy and economic efficiency in grazing dairy systems under alternative intensification strategies

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ABSTRACT

The intensification of dairy systems, or the process of increasing milk productivity per unit of land area, can be achieved through various strategies. However, it is debated whether intensification is associated with increased economic and/or environmental efficiency. The aim of this study was to identify alternative intensification strategies for grazing dairy systems and evaluate their economic and energy efficiency. A model for calculating energy inputs and outputs was applied to 30 dairy farms with reliable production and economic records in Uruguay, spanning a wide range of farm features. Milk productivity averaged 3819 l.ha^{-1} year^{-1} (ranging from 1512 to 6942), intake of concentrate averaged 0.25 kg l^{-1} of milk (ranging from 0.03 to 0.38), fossil energy use averaged 3.96 MJ kg^{-1} (ranging from 1.9 to 9.1) and farm net income averaged $317\ \text{U\$D ha}^{-1}\ \text{year}^{-1}$ (ranging from 136 to 748). Using a numerical classification procedure, four farm clusters that represent different technological, production, and efficiency situations for grazing dairy farms were identified, associated with the differential use of pastures and concentrates. Although increasing used of concentrates in diets was associated with higher milk productivity, and sometimes higher economic performance, it was consistently negatively associated with energy efficiency. Dairy farms with a higher proportion of pasture consumption achieved higher efficiency of utilization of feed concentrates (higher kg milk/kg concentrate) and thus used less fossil energy per liter of milk. These results suggest that sustainable intensification of grazing dairy systems should rely on efficient utilization of pastures rather than just increasing concentrate intake.

1. Introduction

The growth in global population and income has increased demand for food production and consumption, especially animal proteins (Ranganathan et al., 2016). The intensification of livestock systems is the process of increasing milk or meat productivity per unit of land area, and it has been proposed as the necessary path to sustain humanity (Herrero et al., 2016). Intensification can be achieved through various strategies. Conventional intensification of livestock production systems has been achieved by increasing the number of dairy cattle per hectare of land, the acquisition of genetically improved cattle, and the increase in concentrates in the diets (Caviglia-Harris, 2005) supported by use of inputs such as fertilizers, pesticides, and fuel to increase grain and forage yields (Alexandratos and Bruinsma, 2012). This intensification strategy based on inputs and high fossil energy use can result in serious environmental impacts. The emission of greenhouse gases by combustion of fossil fuels, emissions from nitrogen fertilizers, and enteric methane from cattle significantly contributes to climate change (Meul et al., 2007). Soil erosion, nutrient leaching, water contamination and eutrophication of water bodies, are other environmental impacts associated with conventional intensification based on higher use of annual crops and inputs (Modernel et al., 2013; Picasso et al., 2014).

The rising costs of livestock inputs and low prices of products entailed a lower profit margin for producers. Increased productivity through investment in technology (inputs and capital) was the way to increase production and improve the profitability of farming systems (Dartt et al., 1999; Somda et al., 2005). In response to environmental and social problems generated by this model, ecological intensification (Tittonell, 2014), appears as a sustainable alternative, integrating environmental indicators and adding value to the products, through exploiting ecological mechanisms that underlie the productivity, stability and resilience, including the balance between feedstuff (grains) and pasture management (Hanson et al., 1998; Parker et al., 1992). This alternative seeks to develop sustainable production systems that reduce consumption of fossil energy and generate better economic results

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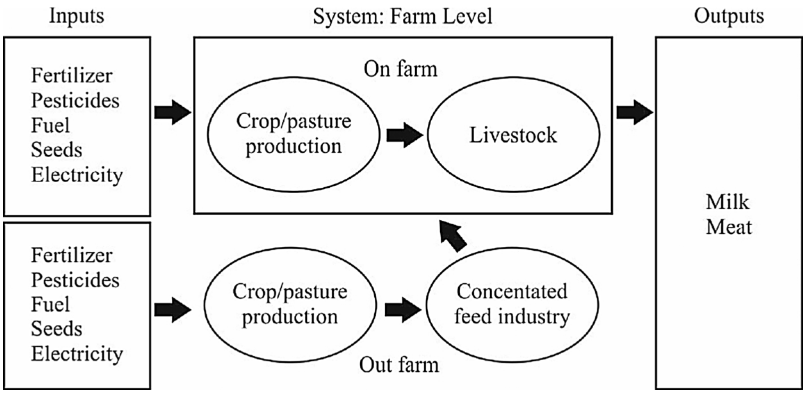

Fig. 1. Model of the system used to quantify the energy inputs and outputs at the farm level.

(Dalgaard et al., 2001; McLaughlin et al., 2000), which would also result in lower emissions of greenhouse gases (Dalgaard et al., 2001; Doucet, 2008; Meul et al., 2007) therefore mitigating climate change.

Grazing is the basis of the dairy production systems in South America, with varying levels of supplementation with conserved forages (Franzluebbers et al., 2014; Ostrowski and Deblitz, 2001). The intensification of dairy systems associated with the use of concentrates and reserves, has increased the productivity of milk with variable effects on the economic cost and energy efficiency. Identifying the best strategy for intensification in dairy appears to be difficult, because while some studies document improved environmental performance of low input systems, other studies contradict this. For instance, Meul et al. (2007) showed reduced energy input from a lower use of fertilizers and concentrates, with 25% increase in milk productivity per ha through a higher milk productivity per cow and a higher stocking rate. Several studies agree that fuel, electricity, fertilizer and animal feed together represent the main part of the total energy consumption (Cederberg and Flysjo, 2004; Cederberg and Mattsson, 2000; Kraatz, 2012; O'Brien et al., 2012; Rabier et al., 2010). Oudshoorn et al. (2011) concluded that minimizing local as well as global environmental impacts did not have an economic trade-off. On the other hand, Alvarez et al. (2008) showed that intensive farms produced at a lower average total cost and presented greater levels of efficiency than extensive farms. Basset-Mens et al. (2009) demonstrated that the high inputs systems can be more profitable when milk price is high and maize silage cost is low but the low inputs systems are more profitable when milk price is low and maize silage cost is high. Therefore, it appears from the previous literature that the relationship between environmental and economic efficiency depends on the dairy systems considered, the region, and the management practices analyzed. The aim of this study was to identify different intensification strategies for grazing dairy farms and evaluate the relationship between productivity, fossil energy consumption per kg of milk (FECK) and economic outcome, using a group of Uruguay dairy farms as a case study.

2. Materials and methods

2.1. Dairy systems database

In Uruguay, dairy cows are usually fed sown pastures of mixtures of grasses and legumes year round, supplementing the diet with corn grain and/or sorghum and silage to maintain milk production during winter when pasture production is poor. These silages are generally produced on the same dairy farm. During milking time, the cows are fed concentrates to satisfy the nutritional requirements of their expected level of production. Dairy cattle are predominantly Holstein breed. The 2009–10 average productivity of Uruguay was 4334 l cow^{-1} and 2410 l ha^{-1} per hectare (DIEA, 2010). and the average annual precipitation in the area was 1100 mm with a maximum temperature of 27° Celsius and minimum 4° Celsius (INIA, 2010).

The farms database for this study was obtained from the productive and economic records of 30 dairy farms remitting their milk to CONAPROLE, the major dairy industry of the country, for the 2009–2010 fiscal year, which was an average climate year. Farms were located in the southern region of Uruguay, in the departments of Colonia, San José, Canelones, and Maldonado. Farms were included in the study because they had reliable records and a broad range of milk productivity, in order to explore the diversity of production strategies. Data from milk productivity per hectare (MPH, l ha^{-1}), milk productivity per cow (MPC, l cow^{-1}), stocking rate (SR, cow ha^{-1}), herd efficiency (number of milking cows/total stock, HE, %), total dry matter intake per cow per year (DMI, kg cow^{-1}), concentrate intake per liter of milk (CL, kg l^{-1}), concentrate intake per cow per year (CC, kg cow^{-1}), proportion of the total intake from concentrate (PIC), proportion of the total intake from pasture (PIP), and proportion of the total intake from silage (PIS), were obtained from the records of each producer. Actual pasture yields were not recorded, and pasture intake per cow is estimated by difference.

2.2. Energy model

The Agroenergía model proposed by Llanos et al. (2013) was used for energy calculations. The model estimates energy inputs and outputs using energy coefficients from international literature and also local coefficients adjusted to the conditions of Uruguay. The model accounts for the input of fossil energy used in different activities within the farm (feed production in pasture or annual crops and feed purchased outside the farm, Fig. 1). The model uses the Hetz and Barrios (1997) methodology to quantify the energy costs of machinery operations per unit area (MJ ha^{-1}), with the coefficients presented by ASAE (1993) and Fluck (1985), for the use of machinery for feed production produced within the farm and bought off farm. For activities within the farm and feed purchased off-farm fossil energy from fuels and agrochemicals (fertilizers, herbicides, and pesticides) were added (Fig. 1). Fossil energy consumption per liter of milk (FECL, MJ.l^{-1}) was calculated.

As outputs the model considers the energy value of milk and meat. The energy value of milk (EM) was calculated from the equation based on the percentages of fat (%F) and milk protein (%P) for each farm: $EM = 40.72\,(\%F) + 22.65\,(\%P) + 102.7$ (Tyrrell and Reid, 1965). The energy value of the meat was calculated from the weight of the different tissues by animal category (García, 1997) and the tissue energy value proposed by Marletta and Carnovale (2000). The main energy parameters used in the Agroenergía model are presented in Table 1 (Llanos et al., 2013).

In order to compare alternative systems of production with previous studies in the literature, our results were transformed to the units of 1 kg energy corrected milk (ECM) and 1 kg fat and protein corrected milk (FPCM) by the following equations: $\text{kg ECM} = \text{kg milk}\,[0.25 + 0.122(\%F) + 0.077(\%P)]$ (Sjaunja et al., 1990) and $\text{kg FPCM} = \text{kg milk}\,[0.337 + 0.116(\%F) + 0.06(\%P)]$ (FAO, 2010).

Table 1
Criteria and energy coefficients used to calculate fossil energy included in the model Agroenergía (Llanos et al., 2013).

Input (unit)	Energy (MJ/ unit)	Criteria	Reference
Diesel (l)	38.5	Calorific value of diesel used in Uruguay, analyzed by bomb calorimeter.	(Ministerio de Industria Energía y Minería, 2010)
Electricity (kW.h)	1.6	Represents 31% of electricity produced from petroleum	(Ministerio de Industria Energía y Minería, 2010)
Herbicides (kg) Insecticides (kg) Fungicides (kg)	266.6 284.8 288.9	Include the formulation of the active compounds in oils, powders or granules, packaging and transport.	(West and Marland, 2002)
Urea (kg) Ammonium nitrate (kg) Mono Ammonium Phosphate (kg) Triple superphosphate (kg)	54 46.6 4.3 7	IFA simplified model uses natural gas as a source of ammonia production (80% of world production).	(Kongshaug, 1998)
Sorghum seeds (kg) Wheat seeds (kg) Corn seeds (kg) Red clover seeds (kg) Ryegrass seeds (kg)	43.5 6.6 53.3 87 27.4	Include cleaning and packaging of the seed. It consists of a 50, 20, and 30% mixture of fuel oil, natural gas and electricity, respectively.	(West and Marland, 2002)

2.3. Economic analysis

Farm purchases and sales records were kept by farmers every month, and converted using the monthly dollar exchange rate for fiscal year 2009–2010. The net income per hectare (NI, USD ha^{-1}) was calculated from the gross economic product per hectare (GP, USD ha^{-1}) minus total costs of inputs per hectare (TC, USD ha^{-1}), without accounting for financial interest or land rent. The gross economic product per hectare (GP, USD ha^{-1}) was the sale of milk and meat adjusted at the price of milk and meat using the monthly dollar exchange rate. The total cost of inputs per hectare (TC, USD ha^{-1}) included feed costs, operating costs (electricity, labor, animal health, repair and maintenance of milking equipment) and structural costs (repair and maintenance barn, housing, vehicles and taxes) at the monthly exchange rate. The Input over Output ratio (I/O) was calculated dividing the gross economic product (GP) by total costs of inputs (TC), and represents a measure of economic efficiency.

2.4. Statistical analysis

The correlation matrix was calculated with all production, energy and economic variables with two objectives: first to identify collinearity (variables that are highly correlated) before performing the multivariate analysis, and second to identify which variables are most associated with fossil energy use. Principal Component Analysis was conducted using variables that were not collinear to graphically explore the relationship between the variables. The variables included in the analysis were: proportion of total intake from pasture (PIP), net income per hectare (NI), milk productivity per hectare (MPH), concentrate intake per cow per year (CC) and fossil energy consumption per kg of milk (FECK). A numerical classification in clusters was performed using Ward's algorithm and Euclidean distances using the same variables used for the Principal Components Analysis. Analysis of variance (ANOVA) was performed using clusters as classification variable. Groups were considered different for each variable only when the P value for the ANOVA was smaller than 0.05. Tukey multiple comparison tests were conducted for those variables with significant differences detected in the ANOVA, in order to identify which groups were different for each variable. All analyses were performed using Infostat (2012) software.

3. Results

The mean and dispersion of the main variables analyzed on 30 dairy farms are shown in Table 2.

Milk productivity per hectare (MPH) and milk productivity per cow (MPC) were positively correlated to dietary variables associated of concentrated feed such as concentrate intake per liter of milk (CL), concentrate intake per cow (CC) and proportion of the total intake from concentrate (PIC), but negatively associated with the proportion of total intake from pasture (PIP). Productivity was also positively correlated to economic variables: gross economic product per hectare (GP) and total costs of inputs per hectare (TC) (Table 3).

Gross economic product per hectare (GP) and total costs of inputs per hectare (TC) were positively correlated with dietary variables associated with the use of concentrates such as concentrate intake per liter of milk (CL), concentrate intake per cow per year (CC) and proportion of the total intake from concentrate (PIC) and negatively correlated with proportion of intake from pasture (PIP) (Table 3).

The Fossil energy consumption per kg of milk (FECK) was positively correlated only with the dietary variables associated with concentrate intake per liter of milk (CL), concentrate intake per cow per year (CC), concentrate intake per liter of milk (CL), and proportion of the total intake from concentrate (PIC) (Table 3). Proportion of intake from pasture (PIP) was negatively correlated with fossil energy consumption per kg of milk (FECK).

The two principal components explained 80% of the total variability of the observations (principal component 1: 57%, and principal component 2: 23%, Fig. 2). As the eigenvalues show (Table 4) Principal Component 1 was positively associated with milk productivity per hectare (MPH), and concentrate intake per cow (CC), and negatively associated with proportion of the total intake from pasture (PIP). Principal Component 2 was positively associated with net income per hectare (NI), and negatively associated with fossil energy consumption per kg of milk (FECK).

A cluster analysis using these five production, nutritional, economic and energy variables was performed, resulting in four groups (Table 5). Group 1 (G1) was comprised by dairy farms which base their production on the use of pastures with low herd efficiency and low use of concentrates, allowing a low consumption of fossil energy, but low milk productivity per hectare. Group 2 (G2) had higher productivity than the G1 due to increased milk productivity per cow, being associated with greater use of concentrate per liter of milk and concentrate intake per cow per year. Group 3 (G3) had higher milk productivity per hectare by high milk productivity per cow using the same proportion of the total intake from concentrate (PIC) in the diet and a higher stocking rate (SR), obtaining good productive and economic results. Group 4 (G4) has highest indicators of productivity, based on a higher concentrate intake per liter of milk, concentrate intake per cow per year and less

Table 2
Mean, coefficient of variation (CV), minimum (Min) and maximum (Max) of the production, energy and economic variables for 30 grazing dairy farms in southern Uruguay. All variables are calculated for one year.

Variable	Units	Mean	CV(%)	Min	Max
Farm area	ha	358	94	46	1448
Milk productivity per hectare (MPH)	l ha^{-1} year^{-1}	3819	38	1512	6942
Milk productivity per cow (MPC)	l cow^{-1} year^{-1}	5492	21	2758	8581
Stocking rate (SR)	cow ha^{-1}	0.7	28	0.36	1.22
Herd efficiency (HE)	Milking cows/stock	0.58	17	0.35	0.81
Concentrate intake per liter of milk (CL)	kg l^{-1}	0.25	31	0.03	0.38
Total dry matter intake per cow per year (DMI)	kg cow^{-1} year^{-1}	7701	16	5252	12281
Concentrate intake per cow per year (CC)	kg cow^{-1}year^{-1}	1471	46	95	3385
Proportion of total intake from concentrate (PIC)		0.2	49	0.02	0.54
Proportion of total intake from pasture (PIP)		0.59	24	0.26	0.8
Proportion of total intake from silage (PIS)		0.22	42	0.07	0.37
Net income per hectare (NI)	USD ha^{-1} year^{-1}	317	41	136	748
Gross economic product per hectare (GP)	USD ha^{-1} year^{-1}	1140	34	594	2011
Total costs of inputs per hectare (TC)[a]	USD ha^{-1} year^{-1}	822	40	315	1614
Input over Output ratio (I/O)		0.71	12	0.53	0.85
Fossil energy consumption per kg of milk (FECK)[b]	MJ kg^{-1}	3.96	47	1.9	9.12

[a] Production costs per hectare of milk and meat without interest or rent from the farm.

[b] Mega Joule units from Fossil Energy including the use of chemicals, fuel, energy fixed in machinery, agricultural activities within the farm and feed purchased outside the farm, calculated with the model Agroenergía (Llanos et al., 2013).

proportion of the total intake from pasture, showing an increased consumption of fossil energy consumption per kg of milk, and better economic results than group 1 and 2 but not significantly different than group 3 (Table 5).

4. Discussion

Intensification of dairy farms based on increasing the proportion of the total intake from concentrate consistently increased production costs and sometimes (but not always) increased net income per hectare. At the same time this intensification consistently increases fossil energy consumption per unit of milk. On the contrary, farms that use higher proportion of pasture in the diets have a more efficient use of concentrate feed (as the lower the substitution rate the higher the milk response to supplements, Bargo et al., 2003), make less fossil energy use and can achieve good economic income, such as farms from group 3 (Table 5). These results are consistent with those presented by Parker et al. (1992); Dartt et al. (1999); Somda et al. (2005). The milk production response determines whether the use of concentrates is cost-effective based on the prices of milk and concentrates. The fat content of milk is reduced when cows are grazing pastures compared with that achieved with concentrated feedstuff, but the economic impact of changes in milk composition depends on the relative prices paid by the milk industry (Parker et al., 1992). In our case there was no difference in net income from fat and protein milk in different groups (data not shown), implying that the increase in energy and protein content of feed concentrate does not outweigh the economic costs obtained in production. However, in order to make an economic assessment, other additional factors, such as increased rates of livestock on the farm, improved pasture utilization, reproduction, duration of lactation should be considered (Bargo et al., 2003).

The finding that fossil energy consumption is positively associated with increased concentrate use, is consistent with previous findings from international literature (Table 6). These studies represent a variety of milk production systems and climatic conditions; hence, the large differences in results across studies. Based on data from two relatively large dairy farms in the west of Sweden, Cederberg and Mattsson (2000) estimated higher energy use in conventional systems versus organic systems (with increased pasture use) with more than double milk production per hectare in the conventional farm versus the organic

Table 3
Pearson correlation coefficient (r, below the diagonal) and the level of significance (P, above the diagonal) for simple linear correlations between productive variables, feed, economic and energy of 30 grazing dairy farms form southern Uruguay. Significant correlation values are shown in bold (P < 0.05).

	MPH	MPC	SR	HE	CL	DMI	CC	PIC	PIP	PIS	NI	GP	TC	I/O	FECK
MPH	1	< **0.01**	< **0.01**	< **0.01**	< **0.01**	0.13	< **0.01**	< **0.01**	< **0.01**	< **0.01**	< **0.01**	< **0.01**	< **0.01**	0.06	0.26
MPC	**0.72**	1	0.55	< **0.01**	< **0.01**	< **0.01**	< **0.01**	< **0.01**	< **0.01**	0.05	0.02	< **0.01**	< **0.01**	0.39	0.08
SR	**0.76**	0.11	1	< **0.01**	0.46	0.26	0.18	0.09	0.02	0.06	0.12	< **0.01**	< **0.01**	0.03	0.93
HE	**0.77**	**0.75**	**0.46**	1	< **0.01**	0.12	< **0.01**	< **0.01**	< **0.01**	< **0.01**	0.16	< **0.01**	< **0.01**	0.03	0.07
CL	**0.48**	**0.6**	0.14	**0.56**	1	< **0.01**	< **0.01**	< **0.01**	< **0.01**	0.18	0.52	< **0.01**	< **0.01**	0.12	< **0.01**
DMI	0.28	**0.66**	−0.21	0.29	**0.53**	1	< **0.01**	< **0.01**	0.04	0.5	0.91	0.05	0.02	0.4	0.42
CC	**0.72**	**0.85**	0.25	**0.78**	**0.87**	**0.67**	1	< **0.01**	< **0.01**	0.06	0.2	< **0.01**	< **0.01**	0.05	< **0.01**
PIC	**0.74**	**0.81**	0.32	**0.8**	**0.9**	**0.55**	**0.97**	1	< **0.01**	0.04	0.16	< **0.01**	< **0.01**	0.07	< **0.01**
PIP	**−0.71**	**−0.68**	−0.42	**−0.8**	**−0.65**	−0.38	**−0.76**	**−0.8**	1	< **0.01**	0.38	< **0.01**	< **0.01**	0.02	< **0.01**
PIS	**0.45**	0.36	0.35	**0.54**	0.25	0.13	0.35	0.38	**−0.86**	1	0.84	0.04	< **0.01**	0.08	0.08
NI	**0.5**	0.44	0.29	0.26	0.12	0.02	0.24	0.26	−0.17	0.04	1	< **0.01**	0.11	< **0.01**	0.78
GP	**0.96**	**0.74**	**0.7**	**0.73**	**0.49**	0.36	**0.73**	**0.72**	**−0.65**	0.39	**0.59**	1	< **0.01**	0.14	0.39
TC	**0.94**	**0.7**	**0.71**	**0.76**	**0.52**	0.41	**0.76**	**0.74**	**−0.7**	**0.44**	0.3	**0.95**	1	< **0.01**	0.26
I/O	0.35	0.16	0.39	0.39	0.29	0.16	0.36	0.34	−0.41	0.33	**−0.56**	0.28	**0.55**	1	0.09
FECK	0.21	0.32	0.02	0.34	**0.47**	0.15	**0.44**	**0.45**	**−0.47**	0.32	−0.05	0.16	0.21	0.31	1

MPH = milk productivity per hectare; MPC = milk productivity per cow; SR = stocking rate; HE = herd efficiency; CL = concentrate intake per liter of milk; DMI = total dry matter intake per cow per year; CC = concentrate intake per cow per year; PIC = proportion of total intake from concentrate; PIP = proportion of total intake from pasture; PIS = proportion of total intake from silage; NI = net income per hectare; GP = gross economic product per hectare; TC = total costs of inputs per hectare; I/O = input over Output ratio; FECK = fossil energy consumption per kg of milk.

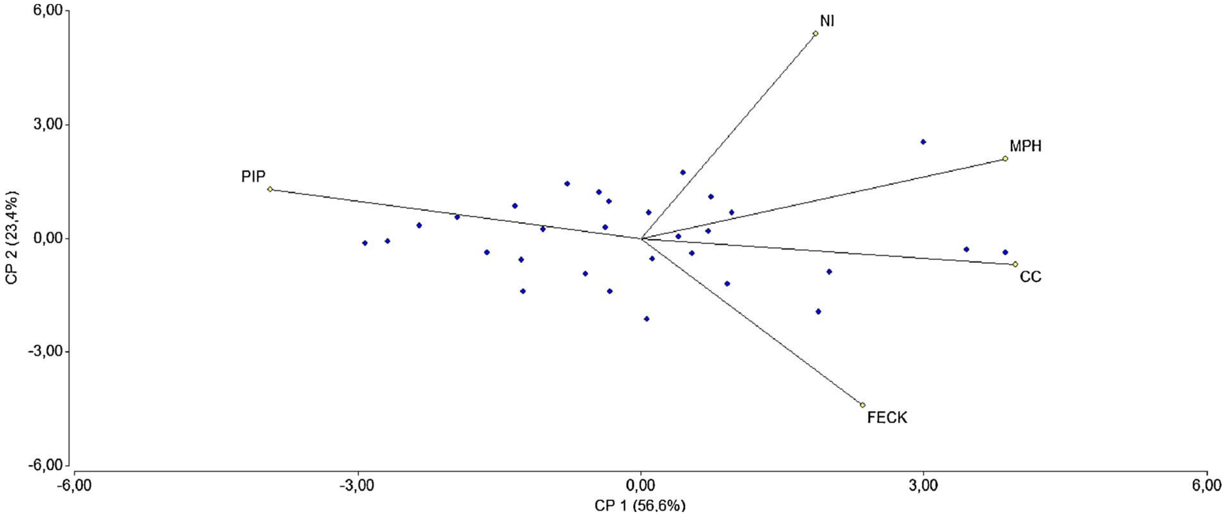

Fig. 2. Principal Component Analysis showing five variables (open dots and lines): proportion of the total intake from pasture (PIP), net income per hectare (NI), milk productivity per hectare (MPH), concentrate intake per cow per year (CC) and Fossil energy consumption per kg of milk (FECK) for 30 grazing dairy production systems (closed dots) in Uruguay.

Table 4
Eigenvalues for the principal components 1 and 2 for 30 dairy farms in Uruguay.

	Eigenvalues	
Descriptive farm variables	PC1	PC2
Milk productivity per hectare (MPH)	0.52	0.28
Proportion of the total intake from pasture (PIP)	−0.53	0.17
Concentrate intake per cow per year (CC)	0.53	−0.09
Net income per hectare (NI)	0.25	0.73
Fossil energy consumption per kg of milk (FECK)	0.32	−0.6

farm. Another paper by Cederberg and Flysjo (2004) studied 23 dairy farms in the west of Sweden, also obtained similar results. In the Netherlands, Thomassen et al. (2008) found that the energy use of 10 conventional commercial dairy farms was higher than the one of 11 organic dairy farms (Table 6). They concluded that feeding more feed produced on farm, feeding less concentrates, and using no pesticides and artificial fertilizers resulted in a lower energy use per kg FPCM (Thomassen et al., 2008). The results presented by O'Brien et al. (2012) showed that the non-renewable energy use of a confinement dairy farm was almost double the one of an intensively grazed seasonal grass-based dairy system in Ireland (Table 6). In a recently published study, Pagani et al. (2016) compared grain based versus forage based dairy farms in Italy and United States, finding that forage based farms had lower energy use than grain based (Table 6). Therefore, our results agree with previous literature that farms with higher degree of intensification based on concentrated feed use more fossil energy per unit of milk produced.

Although the previous literature has focused on comparisons between confined and pasture based or organic systems, our study focused on analyzing an intensification gradient within grazing dairy systems, which are still the large majority of dairy systems in developing

Table 5
Means of production, feed, energy and economic variables for four groups of farms obtained by numerical classification of 30 grazing dairy production systems in Uruguay. Means followed by the same letter are not different between groups (Tukey $P < 0.05$). A significance value for the ANOVA between groups is shown (p-value).

Variable	Units	Group				
		G1	G2	G3	G4	p-value
Number of farms (n)		4	9	11	6	
Farm area	ha	376	553	271	208	0.17
Milk productivity per hectare (MPH)	$l\ ha^{-1}\ year^{-1}$	2220 C	2880 BC	4258 AB	5484 A	< 0.01
Milk productivity per cow (MPC)	$l\ cow^{-1}\ year^{-1}$	4015 C	5144 B	5505 B	6975 A	< 0.01
Stocking rate (SR)	$cow\ ha^{-1}$	0.59	0.58	0.79	0.78	0.03
Herd efficiency (HE)	Milking cows/stock	0.45 C	0.55 BC	0.59 B	0.70 A	< 0.01
Concentrate intake per liter of milk (CL)	$kg\ l^{-1}$	0.14 B	0.25 A	0.24 A	0.33 A	< 0.01
Total dry matter intake per cow per year (DMI)	$kg\ cow^{-1}\ year^{-1}$	7410	7633	7231	8858	0.06
Concentrate intake per cow per year (CC)	$kg\ cow^{-1}\ year^{-1}$	639– C	1321 B	1358 B	2455 A	< 0.01
Pasture consumed (DM) per ha per year	$tt\ ha^{-1}\ year^{-1}$	5845 A	4626 AB	4330 B	3948 B	0.03
Proportion of total intake from concentrate (PIC)		0.08 C	0.17 B	0.19 B	0.30 A	< 0.01
Proportion of total intake from pasture (PIP)		0.79 A	0.60 B	0.60 B	0.43 C	< 0.01
Proportion of total intake from silage (PIS)		0.13 B	0.22 AB	0.22 AB	0.27 A	0.09
Net income per hectare (NI)	$USD\ ha^{-1}\ year^{-1}$	230 AB	225 B	386 AB	387 A	< 0.01
Gross economic product per hectare (GP)	$USD\ ha^{-1}\ year^{-1}$	691 C	900 BC	1264 AB	1567 A	< 0.01
Total costs of inputs per hectare (TC)[a]	$USD\ ha^{-1}\ year^{-1}$	461 C	675 BC	878 AB	1179 A	< 0.01
Input over Output ratio (I/O)		0.66	0.75	0.68	0.75	0.15
Fossil energy consumption per kg of milk	$MJ\ kg^{-1}$	2.02 C	4.51 AB	2.93 BC	6.33 A	< 0.01
Fossil energy consumption per kg of energy corrected milk	$MJ\ kg\ ECM^{-1}$	2.17 C	4.76 AB	3.02 BC	6.57 A	< 0.01
Fossil energy consumption per kg of fat and protein corrected milk	$MJ\ kg\ FPCM^{-1}$	2.14 C	4.71 AB	2.99 BC	6.52 A	< 0.01

Mega Joule units from Fossil Energy including the use of chemicals, fuels, energy fixed in machinery, agricultural activities within the farm and feed purchased outside the farm calculated with the model Agroenergía (Llanos et al., 2013).

[a] Production costs per hectare of milk and meat without interest or rent from the farm.

Table 6

Comparison of cow feed, milk production and energy consumption in different type of production systems for assessment of milk production of selected studies, gathered by functional unit.

Reference and country	Type of System	Feed description (per cow basis)	Milk Production	Total Energy (Fossil energy)	Unit
Cederberg and Mattsson (2000) Sweden	Conventional	2267 kg grass silage, 687 kg pressed beet pulp, 1531 kg concentrate feed, approx. 350 kg pasture	7415 kg ECM ha^{-1}	3.55	Mj kg ECM^{-1}
	Organic	1869 kg silage 1355 kg hay, 775 kg pasture, 1000 kg peas, 343 kg concentrate feed	3297 kg ECM ha^{-1}	2.51	Mj kg ECM^{-1}
Thomassen et al. (2008) Netherlands	Conventional	Purchased concentrates (maize gluten meal, beet pulp, and palm kernel meal) plus on farm grains and pastures	14713 kg FPCM ha^{-1}	5.0	Mj kg $FPCM^{-1}$
	Organic	Purchased concentrates (organic kernel meal, wheat, triticale, lucerne, and lupines) plus on farm grains and pastures	8937 kg FPCM ha^{-1}	3.1	Mj kg $FPCM^{-1}$
O'Brien et al. (2012) Ireland	Grass	Concentrate 370 kg DM/cow per year and grass 4093 kg DM/cow per year	6639 kg FPCM/cow per year	2.3	Mj kg $FPCM^{-1}$
	Confinement	Concentrate 2865 kg DM/cow per year and no grass	8040 kg FPCM/cow per year	3.9	Mj kg $FPCM^{-1}$
Pagani et al. (2016) Italy and USA	Grain based	Cereals, soy and other by-products constitute more than 40% of diet	10693 kg ECM cow^{-1} $year^{-1}$	5.85	Mj kg ECM
			10919 kg FPCM cow^{-1} $year^{-1}$	3.34	Mj kg FPCM
	Forage based	pastures or hay represent more than 60% of diet	5645 kg ECM cow^{-1} $year^{-1}$	3.42	Mj kg ECM
			14626 kg FPCM cow^{-1} $year^{-1}$	3.24	Mj kg FPCM
	Organic	feed and fertilizers follow the regulatory requirement for organic certification.	5328 kg ECM cow^{-1} $year^{-1}$	4.05	Mj kg ECM
		Predominantly pasture and hay based.	7801 kg FPCM cow^{-1} $year^{-1}$	2.0	Mj kg FPCM
Llanos et al. (This study) Uruguay	Group 1	Concentrate 639 kg cow^{-1} $year^{-1}$ and 79% from pasture	2129 kg ECM ha^{-1}, 3896 kg FPCM cow^{-1} $year^{-1}$	2.17 2.14	Mj kg ECM^{-1} Mj kg $FPCM^{-1}$
	Group 2	Concentrate 1321 kg cow^{-1} $year^{-1}$ and 60% from pasture	5443 kg ECM ha^{-1}, 6987 kg FPCM cow^{-1} $year^{-1}$	4.76 4.71	Mj kg ECM^{-1} Mj kg $FPCM^{-1}$
	Group 3	Concentrate 1358 kg cow^{-1} $year^{-1}$ and 60% from pasture	4235 kg ECM.ha^{-1}, 5524 kg FPCM cow^{-1} $year^{-1}$	3.02 2.99	Mj kg ECM^{-1} Mj kg $FPCM^{-1}$
	Group 4	Concentrate 2455 kg cow^{-1} $year^{-1}$ and 43% from pasture	2811 ECM.ha^{-1}, 5080 kg FPCM cow^{-1} $year^{-1}$	6.57 6.52	Mj kg ECM^{-1} Mj kg $FPCM^{-1}$

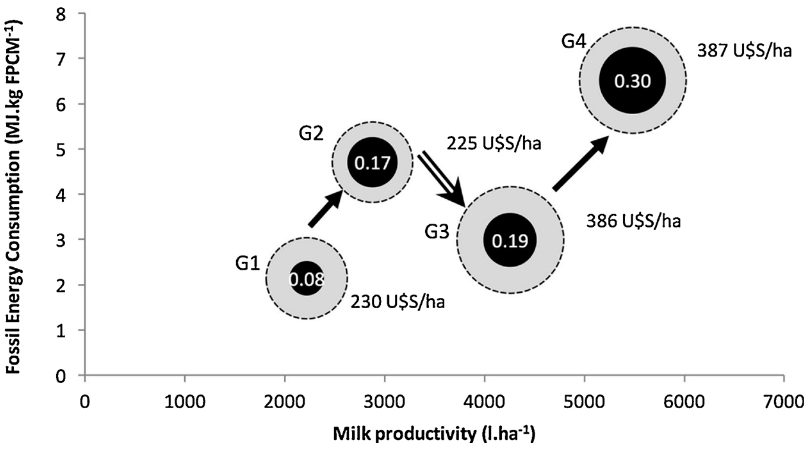

Fig. 3. Intensification trajectory graphs for 4 groups of grazing dairy farms in Uruguay: fossil energy consumption (Y axis) vs. milk productivity (X axis). Area of inner black bubbles represents proportion of total intake from concentrate (values in center of the bubble). Area of external grey dotted-border bubbles represents net income per hectare (values outside bubble, in U$S ha^{-1}). Black solid arrows represent input intensification trajectories, while open (white) arrow represents an ecological intensification trajectory.

countries. We developed an "intensification trajectory" graph (Fig. 3) plotting the environmental performance measured as fossil energy consumption (in the Y axis) versus milk productivity (in the X axis). We added economic performance (net income) and proportion of intake from concentrate as area-sized bubbles in the same plot (Picasso et al., 2017). This intensification trajectory graph is a useful tool to understand the effect of diet changes simultaneously on productivity, environmental, and economic performance. As we move in the X axis from left to right, productivity increases, therefore the production system is under an intensification trajectory. As we move up or down in the Y axis, environmental performance decreases or increases respectively. Therefore, it is possible to identify intensification trajectories with reduced environmental performance, and those with improved environmental performance. For instance, moving from Group 1 to Group 2, the intensification is based in increasing concentrates, but not increasing the stocking rate, which in turn reduces pasture utilization (substitution effect, Bargo et al., 2003). This results in a lack of economic improvement, and a reduction in energy efficiency. This is a clear example of intensification based on inputs. On the contrary, when moving from Group 2 to Group 3, the intensification is not based on increasing concentrate, but on making a more efficient use of pastures, though higher (but not excessive) stocking rate. This trajectory increases both economic performance and energy efficiency, based on taking more advantage of the ecological processes like photosynthesis, biological nitrogen fixation in pastures, and optimal grazing. This is a clear example of ecological intensification. By keeping a higher proportion of the intake from pastures, Group 3 systems maintain the lowest fossil energy consumption (similar to Group 1), but achieve much higher productivity and net income per hectare.

It is noteworthy that further intensification moving from Group 3 to Group 4, through increased use of concentrates (and again without change in stocking rate), does not increase net income, but drastically reduces energy efficiency. This is another example of input intensification. This again can be explained by the substitution effect of pasture by the concentrates (Bargo et al., 2003). Milk production based on increasing amounts of concentrate has been described as curvilinear with decreasing increments, i.e., the increase in milk per kilogram of concentrate decreases as the amount of concentrate increases (Kellaway and Porta, 1993). Other factors can interfere like the quality of the pastures and the genetic value of cows (Peyraud and Delaby, 2001).

Our findings show that without increasing the pasture use (through for instance, increasing stocking rate) even a moderate increase in concentrates does not lead to increasing net incomes. Groups 2 and 4 (Fig. 3) are sub-optimal situations from an economic point of view. Higher use of concentrates provides an opportunity to increase the number of dairy cows, but in the cases analyzed that did not happen. Thus the Group 3 is first of all optimal from an economic point of view, which is the basis for decision making at farms.

A relevant question is whether is it possible to further ecologically intensify dairy systems in Uruguay, and by which means. This requires extending the results of our study to outside the range of the farms we have analyzed, which would be speculative. However, it is reasonable to expect that with increased pasture utilization, via increasing stocking rate, or improved grazing management (e.g., higher forage allowance), it is possible to maintain high levels of pasture in the diet, at high levels of concentrate supplementation also, without substitution of pasture by concentrates. This would increase milk productivity further, while improving energy and economic efficiency. A recent survey of dairy farmers conducted in 2014 by the Uruguayan Dairy Institute (INALE), identified cases of farms which produced over 12000 kg milk/ha, with 35% of concentrated feed intake (INALE, com pers.), based on improved high quality pastures. Although not considered in our analyses because of lack of on farm data, ecological intensification relies also in improving forage quality through the use of improved forage species, and forage mixtures including a high proportion of legumes (like Lucerne, birdsfoot trefoil, red clover, or white clover). Optimal forage and grazing management has a central role in improving the productive, economic, and environmental performance of grazing dairy farms.

5. Conclusions

The sustainable intensification of grazing dairy systems, requires an efficient use of pastures and concentrated feed, so that the proportion of the intake from pastures remains high, and the efficiency of use of concentrate (kg milk/kg concentrate) is also high. Moderately increased use of concentrates from very low levels and the stocking rate simultaneously would improve net incomes, and still maintain or improve energy efficiency. This strategy can achieve at the same time high milk productivity, high net economic income, and low use of fossil energy. The use of models for estimating energy and economic indicators of efficiency across a large number of farming systems can help to analyze the sustainability of technological intensification strategies and identify desirable options.

One of the limitations of this study is that the quality of the feed (forage and concentrates) is not considered because of lack of on farm data. Increased feed quality can increase dry matter intake as well as milk production without increasing the consumption of fossil energy. Another limitation in order to discuss the ecological intensification or a more complete sustainability analysis is the lack of other variables of interest such as greenhouse gas emissions, eutrophication, nutrient balance, etc. Furthermore, a more complete economic analysis should include sensitivity to price fluctuations of inputs, including grain and the barrel of oil. More research is needed to design ecological intensification pathways for grazing dairy systems worldwide.

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