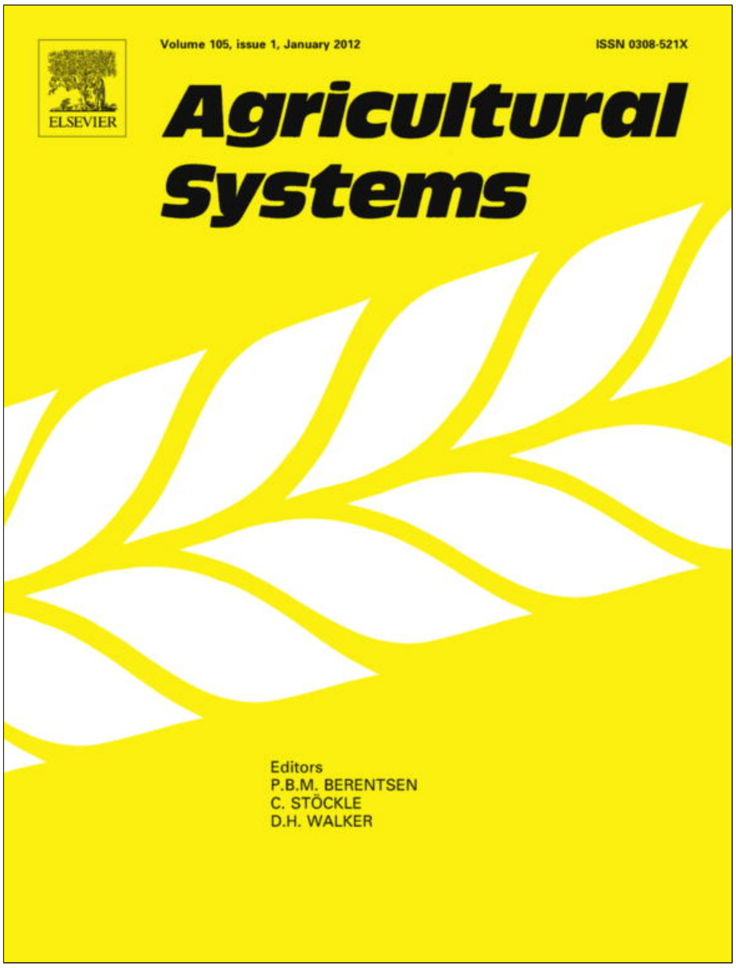
Volume 105, issue 1, January 2012
ISSN 0308-521X
ELSEVIER
Agricultural Systems
Editors
P.B.M. BERENTSEN
C. STÖCKLE
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Agricultural Systems 109 (2012) 35–42

Contents lists available at SciVerse ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Water use in rain-fed farming at different scales in the Pampas of Argentina

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ARTICLE INFO

Article history:
Received 16 December 2010
Received in revised form 8 November 2011
Accepted 22 February 2012

Keywords:
Rainfall use
K_c coefficient
Indicators
Crop water requirements
Cross-scale approach

ABSTRACT

Water use in farming will be an issue of increasing global concern since competition for freshwater among sectors will grow, especially in a water-scarce scenario. Understanding how farming system configurations at different scales affect the partitioning of annual rainfall between production and losses is essential to manage water in rain-fed farming. Data from 198 commercial farms in the Pampas of Argentina were analyzed to assess water use at four different scales: (a) plot, (b) farm, (c) agro-ecological area and (d) whole region. This study offers a novel cross-scale approach and an analytical tool to evaluate water-use relationships in the study region beyond the classical plant–soil–water relationships. Results showed that cattle activities require more water than crops at the plot scale but at broader ones water use patterns are determined largely by cultivation. Given the different performance across scales, results suggest that complex spatial interactions and emerging properties can arise when the analyses are scaled-up from the plot to the regional level. The detection of scale-dependent properties regarding water use will enhance the value of information and knowledge that decision makers operating at different scales need.

1. Introduction

Given the increasing water needs of agriculture and the demand of water from other sectors, one major question is how to economize water use in agricultural production, particularly in countries with limited land and water resources (Debaeke and Aboudrare, 2004). Farmers, agronomists and agro-ecologists should benefit from identifying and assessing alternative farming system designs to optimize the use of water under rain-fed conditions (Connor, 2004).

Water use is affected both by changes in land use and farming intensity in already cultivated lands (Wackernagel and Rees, 1996; Qadir et al., 2003). Given that runoff, drainage and soil evaporation are the main ways of water loss in farming, their minimization is critical for improving water-use efficiency (Sadras, 2003). To address this, it is necessary to understand how different farming configurations affect the partition of rainfall water between productive and non-productive pathways.

The assessment of water requirement for crops and livestock production (Agudelo and Hoekstra, 2001; Markwick, 2007) is necessary to undertake water-use studies in farming systems, especially in water-short regions (Allan, 1996, 1998; Domingo et al., 1999). Given that estimation methods have improved (Allen et al., 1998) and more data on water requirements of plants and animals are available (Hoekstra and Hung, 2002), current analytical approaches have strengthened (Loomis and Connor, 1996) in relation to former studies (Penman, 1948; Thornwaite, 1948).

Studies in Argentina and other countries have explored the agricultural issues of water use by livestock (van Breugel et al., 2010), single crops (Kang et al., 2001; Bandyopadhyay and Mallick, 2003; Sadras, 2003), or more than one crop (Caviglia et al., 2004; Steduto and Albrizio, 2005), mainly at the plot scale. On the other hand, assessments at broader scales (e.g. Eiji Maeda et al., 2011) or integrating crops, cattle, and cattle–crop production are rather uncommon. A good way to assess the conversion of rainfall into agricultural products effectiveness is the estimation of their "water memory" (i.e. all the water needed to produce these products).

Different users (from farmers to policy makers) that make decisions at different hierarchical levels face the challenge of enhancing water productivity at their corresponding scales (Bouman, 2007). While policy-makers generally make decisions that involve broad spatial scales (e.g. a region, a province) and long periods of time (many years), farmers decisions are normally focused on small spatial units (the plot, the farm), and in the short term. Thus, the meaning of water-use assessments and water management differs from one scale to the other. In order to shed light on complex cross-scale performances, the objective of this study was to assess the water-use performance of farming systems at different scales: from the plot to the whole Pampas region.

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0308-521X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.agsy.2012.02.003

2. Materials and methods

2.1. Study area

The Pampas region (30–40°S, 55–65°W), one of the largest prairies of the world (Bilenca and Miñarro, 2004), comprises a large extension of land of around 52 million hectare where a temperate climate with a hot summer predominates. Average temperature varies between 14 °C to the south, and 17 °C to the north. Average annual rainfall, mostly concentrated in spring and summer, ranges from 600 mm in the SW to 1000 mm in the NE (Viglizzo et al., 1995). Rainfall regimes vary across time and space. A long-term cyclical behavior that is notable in the central part of the Pampas caused periodical droughts and floods that affected both crop and cattle production (Viglizzo and Frank, 2006). The variability of rainfall increases from NE where crops predominate, to SW, where lands are mainly allocated to mixed cattle–crop activities (Viglizzo et al., 1997). A noticeable westward expansion of crops occurred during the last four decades in response to a persistent increase of precipitations (Viglizzo et al., 2003).

According to FAO (1989), deep and well-drained soils, which favor continuous cropping of soybean, wheat and maize, predominate on the NE (INTA, 1990). Because of its wind erosion sensitivity and lesser rainfall, western lands are suitable to cattle and cattle–crop production schemes including pastures in rotation with wheat, sunflower and maize (Hall et al., 1992). A similar mixed production scheme involving beef, winter crops and potatoes predominates in SE lands (Solbrig, 1997). Flooding lowland areas on the Salado river watershed are mostly devoted to cattle production on native and introduced perennial pastures. Limitations for crop production in this area are normally associated with shallow soil, soil salinity, poor drainage, and water erosion (Musto, 1979; Casas, 1998).

Given the large rainfall and soil heterogeneity of the region (Satorre, 2001), the region was divided into five agro-ecological areas (Fig. 1): (1) Rolling Pampas, (2) Subhumid Pampas, (3) Semiarid Pampas, (4) Southern Pampas and (5) Flooding Pampas (Soriano et al., 1991; Hall et al., 1992; Viglizzo et al., 2003, 2006). A rough reconstruction of land use history and main characteristics of these areas is presented in Table 1.

2.2. Data sources

In 2002, 198 commercial farms scattered across the five agro-ecological areas were surveyed (Fig. 1). Data were processed and analyzed through a model named Agro-Eco-Index® (Viglizzo et al., 2006), to which a specific water-use indicator was recently included (see Section 2.3). A standardized form allowed the collection of quantitative data from farms and plots. Detailed information on land use (annual crops, annual and perennial pastures, native and cultivated forests and non-productive areas), inputs use, management schemes, crop and cattle productivity, and local meteorological data were recorded. The model provided default figures on uncommon records in farms (e.g. evapotranspiration) when field measurements were missing. Besides the mentioned plot- and farm-level data, records from governmental censuses on land use for years 1960, 1988 and 2002 (INDEC, 2005) were used to calculate indicators at the broader geographical scales. These sources provided information about land allocation to crops and grasslands/pastures, cattle heads, yields, and predominant technology and management practices.

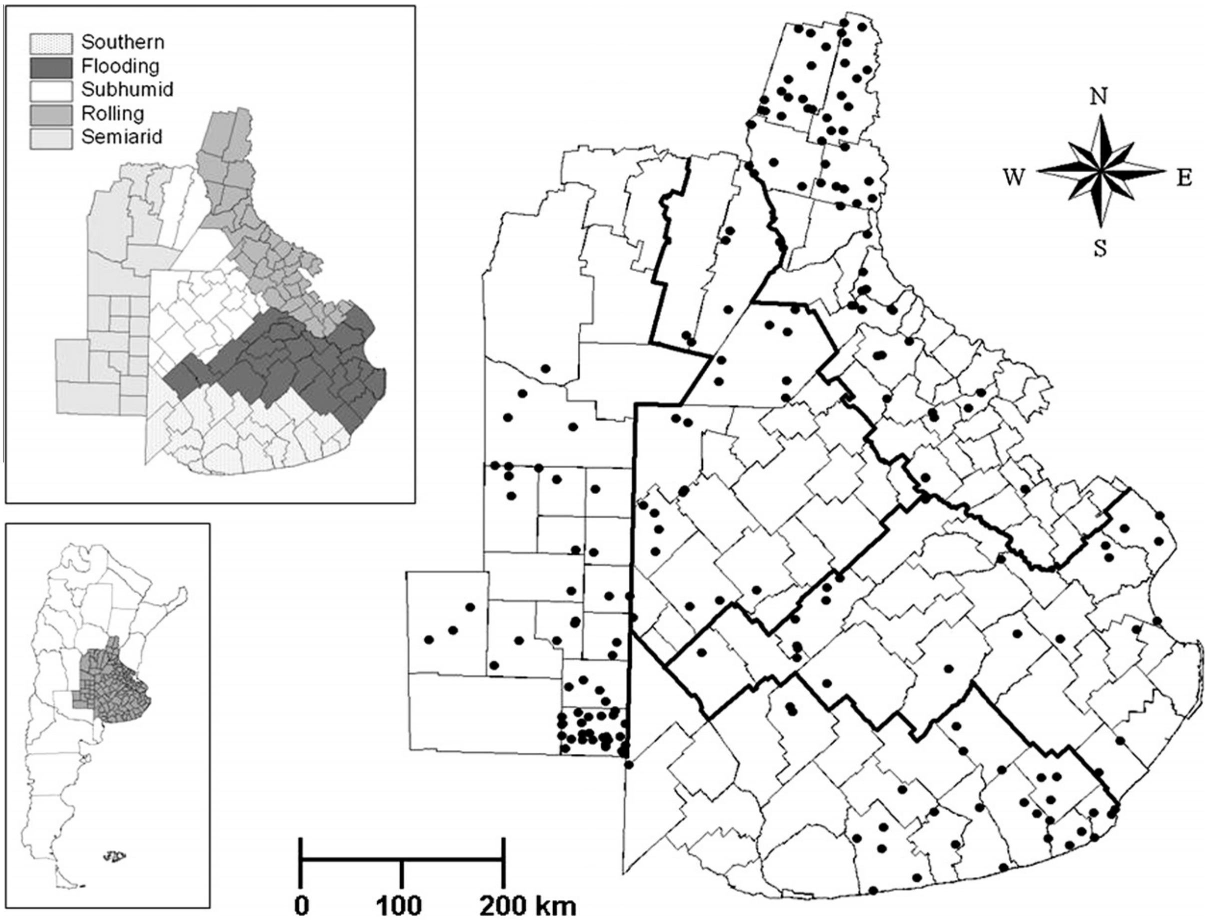

Fig. 1. Location of the 198 surveyed farms in their corresponding agro-ecological areas.

Table 1
Characterization of the Argentine Pampas in the study period.

Agro-ecological area		Land use (%)						Meteorological conditions		Area (Mha)
		Wheat	Maize	Sunflower	Soybean	Beef*	Dairy	Annual PPT (mm)	Annual ETP (mm)	
Southern Pampas	1960	29.1	1.1	1.9	0.0	67.6	0.2	750	1085	8.9
	1988	31.9	3.1	15.1	0.3	49.5	0.1	822	1060	
	2002	37.0	3.6	16.1	5.8	36.7	0.8	1303	962	
Flooding Pampas	1960	14.9	11.7	11.6	0.0	61.4	0.4	635	1084	9.2
	1988	9.1	8.3	8.9	1.4	71.9	0.4	645	1080	
	2002	19.8	7.8	6.5	16.6	48.2	1.1	908	1002	
Rolling Pampas	1960	13.6	16.7	2.9	0.0	66.3	0.5	765	1369	7.7
	1988	16.4	10.9	2.6	30.8	39.1	0.3	840	1336	
	2002	19.1	9.2	0.4	53.0	12.9	5.4	1308	1216	
Semiarid Pampas	1960	15.0	12.0	0.1	0.0	71.6	1.3	476	1501	11.8
	1988	10.1	11.2	2.9	8.4	66.3	1.1	644	1379	
	2002	13.2	8.3	8.0	21.1	45.8	3.6	727	1340	
Subhumid Pampas	1960	16.7	7.7	3.7	0.0	71.4	0.6	627	1360	9.0
	1988	12.0	11.9	4.3	18.5	53.0	0.4	774	1285	
	2002	17.8	12.9	2.4	42.2	21.1	3.6	1022	1207	

References: Land use is the percentage of each activity over the study area (Source: National Institute of Statistics and Censuses of Argentina); PPT = precipitation, ETP = evapotranspiration (Source: National Meteorological Service of Argentina).

* Waste areas (lagoons, rock formations, degraded grasslands) are included in this category.

2.3. Calculation model

Water used for plant growth may be expressed as evapotranspiration (ET), which comprises both evaporation (E) and transpiration (T). The actual ET for a given crop (ET_C) is not simple to determine on the field, so crop water requirements are usually calculated by the standard FAO-56 approach (Allen et al., 1998). The crop coefficient (K_c), introduced by Jensen (1968), corresponds to the ratio between ET_C and the reference ET (ET_0, which corresponds to the atmospheric evaporative demand on a reference grass). Crop coefficient information, which has been empirically determined for many crops, aims to incorporate into the equation the crop type, variety and development stage.

Water used by main crops (WUC, expressed in mm year^{-1}) in the region (wheat, soybean, maize and sunflower) was estimated by multiplying the K_c (dimensionless) of each crop (i) and ET_0 (in mm), both for each month (j), during the evaluated year (Eq. (1)). The monthly K_c values were obtained linearly from the initial (K_{ci}), mid-season (K_{cm}) and late season stage (K_{ce}), considering the crops phenological changes (Allen et al., 1998). On the other hand, local ET_0 values were obtained from Murphy (2008).

$$\mathrm{WUC}_i = \sum_{j=1}^{12} (\mathrm{ET}_{0j} \times K_{cij}) \times \frac{Y_i}{\overline{Y}_i} \tag{1}$$

This approach corresponds to a crop grown under optimal management conditions, including sufficient water supply. The FAO-56 paper recommends adjustments on K_{ci} for less than optimal wetting frequency, and on K_{cm} and K_{ce}, for less than perfect growing conditions or stand characteristics (i.e. relatively poorer conditions of density, height, leaf area, fertility, or vitality). Adjustments on K_c may be done using soil wetting frequency (SWF), crop leaf area index (LAI), effective ground cover (EGC), or the yield response factor (K_y). Although SWF, LAI and EGC may seem better options, because they can be applied at particular phenological stages, the information needed to do this is not easily obtained (at least, not for the extent of this study). In FAO-33 paper (Bentvelsen and Branscheid, 1986), a simple, linear crop–water production function was introduced to predict the reduction in crop yield when crop stress is caused by a shortage of soil water. By inverting this relationship, it is possible to obtain the stress factor (K_s, which is related to K_y, the actual yield, and a maximum yield) needed to adjust K_c for less than perfect growing conditions (Allen et al., 1998). Assuming a unique value of K_y for all crops and pastures, WUC values were adjusted using the proportional difference between actual yields (Y) from field records, and the theoretical yields provided by literature.

On the other hand, estimations of water use in cattle (beef or dairy) production (WUK) for each animal head (k) assumed that the two main ways of water input were drinking water (DW) and water used for feed production (FW, Eq. (2)).

$$\mathrm{WUK} = \sum_{k=1}^{p} (\mathrm{DW}_k + \mathrm{FW}_k) \tag{2}$$

Despite there are factors affecting the daily consumption of drinking water by cattle, like dry matter (DM) intake, animal size, activity, environmental factors, etc. (NRC, 2000), a mean value of 50 L animal^{-1} day^{-1} based on local farmers estimations was adopted for DW. On the other hand, FW was estimated by considering the "water memory" of the food consumed by each animal, i.e. the sum of the water used to produce forage (WUF) and the water used to produce the supplements (WUS, Eq. (3)).

$$\mathrm{FW} = (\mathrm{WUF} + \mathrm{WUS}) \tag{3}$$

In the region, nearly all the cattle are raised through grazing, with only 1.2% finished in pens (INDEC, 2005). Cattle usually graze on pasture, rangeland, winter cereals and/or maize stubble through the whole year. In addition, around 35% of the animals are finished using supplements (INDEC, 2005). Considering these factors, WUF (mm year^{-1}) was estimated for forage crops, pastures and grasslands (Eq. (4)) by following a procedure similar to that of crops. For perennial vegetation, monthly K_c was kept constant at the level of K_{cm}. The contribution of each forage type to the total water use by cattle was estimated through its proportional area (A).

$$\mathrm{WUF} = \sum_{j=1}^{12} \left(\sum_{i=1}^{n} (\mathrm{ET}_{0j} \times Kc_{ij}) \times \frac{\mathrm{CF}_i}{TF_i} \times \frac{A_{ij}}{A} \right) \tag{4}$$

In the same way that in Eq. (1), the forage consumed (CF) by beef or dairy animals to the total annual forage production (TF) ratio was be used as a proxy for the fraction of the actual water used for the production of the consumed forage (van Breugel et al., 2010). Unlike supplementary feeds, that were supplied by farmers, forage intake had to be empirically estimated to correctly assess its contribution to whole cattle diet. Since no records were available in the evaluated farms, the determination of CF was carried out by estimating the food intake demand of cattle heads.

There are many factors influencing food intake in ruminants, including pregnancy stage, water intake, body fat, genetic merit, environmental factors and forage availability (NRC, 1987). Because these factors are not completely understood, current models for predicting intake are empirical by nature (NRC, 2000). The equations found in the literature (ARC, 1980; NRC, 1987, 2000; Fuentes-Pila et al., 2003; Fox et al., 1992; Ellis et al., 2006), rely on mathematical relationships that correspond to biological hypotheses of intake control, but they do not account directly for all the numerous physiological, environmental, and management factors that alter feed intake. However empirical, they are indeed reflective of biological hypothesis, and have been shown to produce results robust enough for tactical management decisions (Pittroff and Kothmann, 2001).

Considering the limitations of this approach, and the variability in the results that can be found for identical feed and animal properties using one or another model (Casasús et al., 2004), two intake prediction equations proposed by the Agricultural Research Council (ARC, 1980), which relate feed intake to dietary energy concentration and live weight, were adapted to estimate CF for beef (Eq. (5)) and dairy (Eq. (6)) cattle.

$$\mathrm{CF_B} = \left(\overbrace{\left(\frac{(24.1 + 106.5 \times q) \times W^{0.75}}{1000}\right)}\mathrm{DM} - S + \frac{(0.0653 + 0.0007 \times W \times (\frac{S \times 100}{\mathrm{DM}}))}{10}\right) \times k \tag{5}$$

$$\mathrm{CF_D} = ((0.135 \times W^{0.75}) + (0.2 \times (P - 16)) \times (-0.44 + 2.6 \times q)) \times k \tag{6}$$

For beef cattle (Eq. (5)), $\mathrm{CF_B}$ was determined as total DM (in kg year^{-1}) intake for each cattle head (k) by using the live weight (W) of animals and the mean metabolizability (q) of the diet, which corresponds to the metabolizable energy to gross energy ratio of forage (dimensionless). Data from type and quantity of supplementary food (S, in kg year^{-1}) collected from the farms' surveys were used to differentiate forage DM from supplement DM, considering the corresponding substitution effect of the latter on forage DM.

For dairy animals, $\mathrm{CF_D}$ was estimated through W, with later adjustments by milk production (P) and q (Eq. (6)). The inclusion of milk output (in L day^{-1}) implies that the prediction corresponds to the DM intake required to sustain a given level of milk yield, which was obtained from the farms' surveys.

On the other hand, WUS values (Eq. (3)) were estimated in mm year^{-1} as the multiplication of the water used in the process of making the supplements (water memory), and the total amount of supplements of each farm. Figures on water memory of supplements were obtained from the literature (Doorenbos et al., 1986; FAO, 1992; Barthèlemy et al., 1993; Renault and Wallender, 2000; Hoekstra and Hung, 2002; Zimmer and Renault, 2002; Hoekstra, 2003).

2.4. Scale issues

The study's data sources accounted for four different scales: first, the assessments described in the previous section were used to analyse data at the (i) plot and the (ii) farm scale, and second, their combination with censuses data was used to approach the broader (iii) agro-ecological and (iv) regional scales.

Results from main crops and cattle activities at the plot scale were expressed in mm year^{-1} in order to allow a proper comparison among figures. Although beef and milk production generally involve a time-dependent rotation among several plots (rangelands, pastures and forage crops), the smaller scale was represented by one single activity at the plot level (i.e. all foraging plots for a given cattle farm were considered one plot).

Water-use values at the plot level were multiplied by the proportional area allocated to each one in order to get whole-farm estimations. Hence, the farm scale corresponded to the integration of various activities (crops, beef and/or dairy) in multiple plots. Taking into account their predominant activities, six farming system types were identified: (i) summer-crops (comprising mainly soybean, maize and sunflower), (ii) summer/winter-crops (mainly wheat, maize and soybean), (iii) beef, (iv) dairy, (v) beef–crop and (vi) dairy–crop (mixed systems). In turn, the 198 farms were classified into one of these categories. Water-use values at the farm scale did not correspond directly to the simple adding up of figures at the plot level. Therefore, the estimation of water use at the farm scale was not the simple result of summing up figures. A number of factors that emerge at this particular scale affects water use at the farm scale, such as double cropping, presence of marginal areas, soil water storage from one season to the other, and cattle foraging on crop residues.

The agro-ecological scale was reconstructed by combining predominant farm-system types in five homogeneous agro-ecological areas (Rolling, Sub-humid, Semiarid, Southern and Flooding Pampas) across the study period. Following a similar logic, the broader regional scale was built through the proportional aggregation of the five agro-ecological areas. To do this, water-use values at the farm level were multiplied by the number and size of farms of each farming system in each one of the 135 administrative districts, according to the census (INDEC, 2005). At the broader spatial scale, the districts were the source of variability. Weighted means and standard deviations were calculated from statistical data provided for each district.

The temporal scale was addressed by replicating the combination of dominant farming systems in three selected years: 1960, which represented the farming conditions of the 1950 decade, when the traditional extensive agricultural model prevailed; 1988, which represented the transition from the traditional to the modern model; and 2002, representing the modern agricultural model extended across the region. Even though three isolated years may not be enough to represent a tendency in precipitation, the selected years are in line with a noticeable precipitation increase in the region reported by Viglizzo et al. (2003).

3. Results and discussion

3.1. The plot and the farm scale

Mean values of water use (mm year^{-1}) for single farming activities (wheat, maize, sunflower, soybean, beef and milk) in the Pampas at the plot scale were compared with a range of reference values supplied by literature (Table 2). With the exception of few studies carried out in semiarid conditions for maize and soybean (Fengrui et al., 2000; Fan et al., 2005), literature values for crops were, in general, higher than those of this study. This is probably because literature data were recorded under different experimental contexts, and very often under optimal growing conditions. Besides, the use of the actual to potential yield ratio probably overestimated the reduction of water use in actual conditions (compared to optimal conditions). Nevertheless, due to the relatively low water requirements (in liters per kg of product) estimated for crops in the Pampas, agricultural production may be more attractive than in other countries, because it consumes less water from rainfall. Therefore, crops like wheat, maize, sunflower and soybean show lower water-use values than those recorded in other regions of the world (Chapagain and Hoekstra, 2004; Aldaya et al., 2010).

Cattle activities showed, as expected, higher water use values ($p < 0.05$) than those of annual crops, which agree with evidence provided by other studies (Barthèlemy et al., 1993; Renault and Wallender, 2000; Hoekstra and Hung, 2002; Hoekstra 2003, 2010). These estimations correspond to cattle that predominately

Table 2
Water use and water requirements in dominant single farming activities in the Argentine Pampas.

Product	n	Water use ($mm\ year^{-1}$)				Water requirements ($L\ kg^{-1}$)	
		Mean		St. dev.	Reference values	Edible product	Dry matter
Wheat	121	186.06	d	83.09	231.7–416.5[a,b,c,d,e,f]	757.45	870.63
Maize	91	543.86	c	207.36	310.1–641.6[a,b,f,g,h]	828.12	951.86
Sunflower	54	221.88	d	108.21	237.8–864.0[h,i,j]	1380.81	1525.76
Soybean	79	343.53	cd	99.92	214.0–798.1[b,d,h]	980.61	1083.55
Beef	131	878.28	b	1169.18	427.5–964.0[h,k,l,m]	27327.46	105,105.62
Milk	78	1116.51	a	1315.95	405.7–750.5[h,m]	6202.61	53,013.76
P-value		<0.0001					

References: St. Dev. = standard deviation; n = sample size; different letters in the same column denote significant differences ($p < 0.05$).
Reference values:
[a] Fan et al. (2005) (Northwest China, semiarid conditions, pan evaporation and rainfall records).
[b] Fengrui et al. (2000) (Northwest China, semiarid conditions, soil water balance and ET).
[c] Bandyopadhyay and Mallick (2003) (Eastern India, irrigated, field water balance and ET).
[d] Caviglia et al. (2004) (Southern pampas of Argentina, rain-fed conditions, soil water balance and meteorological data).
[e] Kang et al. (2001) (Northwest China, irrigated, simulation model).
[f] Jin et al. (1999) (China, semiarid conditions, meteorological data).
[g] Ortega et al. (2004) (Spain, irrigated, simulation model).
[h] Barthèlemy et al. (1993) (California-Egypt, semiarid conditions, calculated from liters of water per kg of product using local mean yields to express them as $mm\ year^{-1}$).
[i] Aboudrare et al. (2006) (Morocco, semiarid conditions).
[j] Steduto and Albrizio (2005) (Southern Italy, irrigated, K_c coefficients).
[k] Pimentel et al. (1997) (global estimation, calculated from liters of water per kg of meat using local mean yields to express it as $mm\ year^{-1}$).
[l] Qassim et al. (2008) (Australia, calculated through the consumption of an irrigated alfalfa pasture, meteorological data).
[m] Renault and Wallender (2000) (California, water requirements).

Table 3
Water use in dominant single farming activities in the Argentine Pampas at the agro-ecological level.

Product	A	Water use ($mm\ year^{-1}$)			n	Product	A	Water use ($mm\ year^{-1}$)			n
		Mean		St. dev.				Mean		St. dev.	
Wheat	S	290.535	a	97.931	23	Soybean	S	307.048	b	156.208	9
	F	159.910	bc	50.990	5		F	329.144	b	23.754	3
	R	169.483	bc	65.187	41		R	335.074	b	90.253	49
	SA	140.212	c	47.362	36		SA	316.072	b	67.4891	4
	SH	189.661	b	33.703	16		SH	407.511	a	88.296	14
	P-value	<0.0001					P-value	0.1014			
Maize	S	565.108	ab	225.511	11	Beef	S	615.393	b	396.431	17
	F	476.477	bc	130.749	6		F	405.316	b	539.555	14
	R	614.026	a	195.758	46		R	1381.500	a	1680.81	41
	SA	331.793	c	121.232	11		SA	452.092	b	447.190	41
	SH	501.258	b	196.873	17		SH	1318.970	ab	1207.150	18
	P-value	0.0006					P-value	0.0006			
Sunflower	S	240.405	b	127.116	17	Milk	S	1366.070	ab	–	1
	F	167.836	b	4.728	4		F	951.483	b	527.204	11
	R	355.529	a	198.071	5		R	2032.130	a	1433.600	35
	SA	192.235	b	57.829	21		SA	133.181	c	189.210	29
	SH	201.268	b	40.784	7		SH	134.201	bc	91.121	2
	P-value	0.0209					P-value	<0.0001			

References: A: Agro-ecological areas: (S) Southern Pampas, (F) Flooding Pampas, (R) Rolling Pampas, (SA) Semi-arid Pampas, (SH) Sub-humid Pampas; St. dev. = standard deviation; n = sample size; Different letters in the same column denote significant differences ($p < 0.05$).

graze on perennial (natural and cultivated) pastures (Hall et al., 1992) which consume water throughout the year. Moreover, the use of supplementary grains and fodder adds extra water to the production process, because of the "water memory" of feeds produced outside the farm. Besides, given that cattle production often consumes extra water (e.g. from groundwater for drinking, farmyard cleaning, milk cooling, etc.), water use values of cattle products, especially in the case of intensive farms, exceeds in average the amount supplied by annual rainfall. Although cattle products demand much more water per kg of product than crops (and per space unit as well), denoting a lower biological efficiency in hydrological terms, it can be argued that grazing cattle is perhaps in the only effective way to harvest rainfall water from sparse vegetation, especially in areas that are not suitable for crop cultivation (Zhang et al., 2001).

Setting aside differences among and within products, values also vary among and within agro-ecological regions (Table 3). As expected, the better the environmental conditions for farming, the greater the water-use values. These differences account for the high standard deviations showed in Table 2, variations that can be confirmed through the range of values presented by results in literature.

No records of water use in integrated farms, combining different production activities (especially mixed systems) were found in the literature to contrast with the results of this study. Water-use performance at the farm scale (Table 4) showed major changes when values were compared to the plot scale, suggesting that there might be factors and interactions triggering emerging properties as water use is scaled-up. Regarding cash crops, values at the farm scale were close to the values that would be expected from the

Table 4
Water use in main systems of production in the Pampas.

Product	n	Water use (mm year^{-1})	
		Mean	St. dev.
Cattle	19	205.42	190.69
Dairy	47	508.57	530.23
Mixed cattle-crop	70	548.63	429.36
Mixed dairy–crop	34	941.79	557.98
Sumer crops	14	462.72	368.14
Summer and winter crops	14	352.89	173.40

References: St. dev. = standard deviation; n = sample size.

combination of values at the plot scale (Table 2). Two opposite factors emerged at this scale: on one side, the inclusion of non-productive areas inside the farms (inner roads, waste areas, fences) should have rendered lower water-use values. On the other side, this decrease in water use was counterbalanced by increased land-use intensity (e.g. more than one crop per year on a given plot), as can be appreciated when the winter-summer crop system is compared with most single crops. As stated by Caviglia et al. (2004), double cropping is a way to increase productivity of resources, including water.

On the other hand, an apparent contradiction aroused in the case of beef and diary which showed highest consumption values at the plot scale, and lowest values at the farm scale. This inconsistency can be explained by at least four reasons: (i) farms normally involve a varied extension of non-productive and waste areas (houses, gardens, inputs stores, machinery parks, lagoons, etc.); (ii) the occupation of plots is not homogeneous throughout the year, especially in marginal areas, both for cattle (grazing and resting periods) and forage crops (rotations with less than one crop per year); (iii) even in cases where one single-activity predominates (e.g. beef production), water use may be biased by other minor activities; and (iv) the irregular distribution of farming activities in the agro-ecological areas (Table 3) absorbs the impact of extreme values when they are scaled-up.

Like it happened with crops, the scale-dependent decrease found in water-use was in some cases compensated by a more efficient land land-use. Mixed systems (beef–crop and milk–crop) showed higher values than "pure" systems (beef and milk), which can be explained by complementary activities making a more efficient use of resources (e.g. cattle feeding on crop residues).

The assessment of water use at the smaller scales (plot and farm) should not be underestimated, especially in the case of land users which make decisions at these scales. Considering that the ecological footprint of water is cause of increasing attention and concern in modern societies, as it also happens with other critical issues such as CO_2 emissions (Wackernagel et al., 2002), it is likely that farmers in the Pampas will be pushed, sooner or later, to measure the water footprint of their products in order to open new markets, or even to keep the traditional ones open.

3.2. The agro-ecological and regional scale

When water-use values for year 2002 at the farm level were scaled-up to the agro-ecological level (Fig. 2), the emergence of new properties seemed to exacerbate the properties that were noticed at the farm scale (Table 4). The maximum and minimum values of water use were found, respectively, in the Flooding and the Rolling Pampas. This behavior is exactly the opposite to what would be expected from the simple process of adding-up the plot-scale (or farm-scale) values (Table 2), because the first one is a typical livestock production area, and in the latter is dominated by the cultivation of annual crops (Table 1). Probably, the vast and highly variable area occupied by water bodies, plus other waste areas such as rock formations (*Tandilia* and *Ventania* systems) in the Flooding Pampas is distorting the expression of water use by single cattle activities. Besides, the climatic conditions for crop production in the Rolling Pampas are more suitable than in the Flooding Pampas (Table 1).

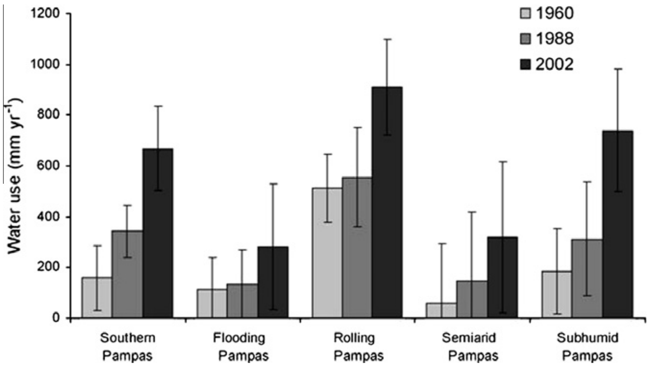

Fig. 2. Water use (mm year^{-1}) at different agro-ecological areas in the Pampas region in the study period. Error bars are standard deviations.

Another example appears in the Semiarid Pampas, where the relatively lower outcomes seem to respond to an interaction between a less favorable climate and the predominant farming systems. At this scale, supplement's related water consumptions for cattle (beef and dairy) were subtracted from water use values to avoid double counting, since most supplements used are produced from yield crops situated close to cattle farms. To a minor extent, this could help to explain the dissimilar behavior between the plot, the farm and the agro-ecological scales.

In relation to 1960 and 1988, the analysis of year 2002 showed a marked and generalized increase of water use across the agro-ecological areas. This can be explained by higher yields due to technology adoption and a more intensive use of land. In absolute terms, this increase was highest in the most productive and intensively cultivated areas: Rolling, Subhumid and Southern Pampas (Table 1). However, in relative terms, this increase was highest in Semiarid Pampas, which is the area that shows the lowest potential for crop and cattle production.

At the broader scale of analysis, mean figures of water use for the whole region evolved from year 1960 to year 2002 rendering values that in the last year were higher than those of literature (Fig. 3). Wallace (2000) has estimated that ET in semi-arid areas can amount to 15–30% of the total water input in rain-fed agriculture, suggesting that the rest of the water is lost as runoff and drainage. Rockstrom (1999), on the other hand, found that only up to 9% of rainfall is used for evapotranspiration in water-scarce regions, and this figure reaches 5% in some parts of Sub-Saharan Africa (Qadir et al., 2003). According to this, the Argentine Pampas seems to be well endowed to produce commodities with a relatively high efficiency in hydrological terms. In rain-fed agriculture, water not used by crops either evaporates, flows over the land, or infiltrates, so only a portion of it may be available for other uses (e.g. aquifer recharge). On the other hand, there is evidence that cultivation may have a strong influence on the dynamics of groundwater and floods in some parts of the Pampas (Viglizzo et al., 2009). In any case, further research on the land use-water resources relationships is needed.

A generalized increase of productivity in the Pampas occurred during the last 40 years in response to cultivation expansion, rainfall increase, and the incorporation of agronomic practices and technologies, such as high-yielding varieties, inputs (fertilizers, pesticides, concentrates), and conservation tillage (Hall et al., 1992; Viglizzo et al., 2003). These changes caused an alteration of water-use patterns and its efficiency in time and space. Beyond the differences in precipitation among the selected years, an even

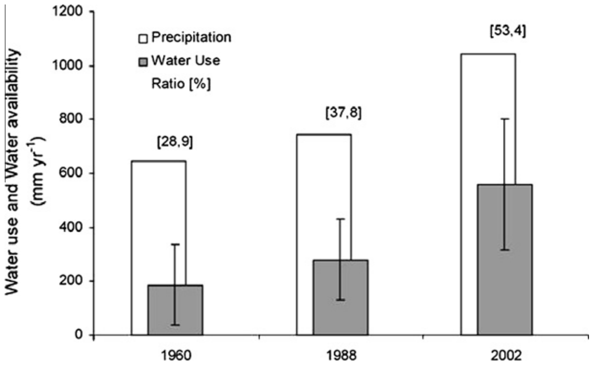

Fig. 3. Precipitation, water use (mm year^{-1}) and water use to precipitation ratio (%, in brackets) of the study period at the Pampas region. Error bars are standard deviations.

higher increase of the water use to precipitation ratio should be noted (Fig. 3). This relationship is an indirect measure of rainfall water-use efficiency, which increased from less than 30 to more than 50%. A sequential combination of land-use change and technology explains such response: First, crops expanded at the expense of the less productive grazing areas (natural grasslands and cultivated pastures); second, modern agronomic practices and technologies were generalized over those croplands (Viglizzo et al., 2003).

Schulze (2000) compiled and described a number of reasons why scale and scaling problems occur in hydrological and ecological systems. Factors like spatial heterogeneity, non-linearity in responses, thresholds, changes in dominant processes at different scales, and the development of emerging properties complicate multi-scale analyses. However, there are several methods of upscaling in natural sciences, from the simple extrapolation of values to the complex integration of models into a broad-scale "summary" model (Ewert et al., 2006). In this paper, up-scaling was done by a combination of "aggregation of input data" (from the plot to the farm scale) and "aggregation of output data" (from the farm to the agro-ecological and regional scales). These choices may result in errors if the processes responses to input variables are non-linear (as is true for most environmental systems) or are cause of cross-scale interactions. Nevertheless, many scaling attempts have been done by following this procedure, because more appropriate methods (like multi-scale modeling) are often restricted by lack of data availability (Ewert et al., 2006). Even considering these issues, results showed that figures and relationships obtained at a given scale cannot directly be scaled-up to broader scales, or scaled-down to smaller scales. Therefore, there is risk of making wrong decisions each time information is handled disregarding the scale at which it should be considered. As stated by Niu et al. (2011), any attempt to upscale water use from leaf to ecosystem to the global scale should be cautious and take into consideration of the diverse response of water use at different levels.

4. Conclusions

The strategic value of water in agriculture in the Pampas demands a cross-scale approach involving the intervention of different categories of decision makers and stakeholders, which operate at different scales. For example: at small scales, land owners and managers should increase their water-use efficiency by keeping in mind the relationships of competition and complementation among crop and cattle activities. At intermediate scales, land users (e.g. land planners, big commercial firms) should look at harmonizing the balance between water resources and the capacity of production systems to use them efficiently. Finally, at the regional scale, the possible competition between agriculture and other sectors on one side, and the possible effects of cultivation on the dynamics of groundwater on the other, will have to be considered by regulatory authorities.

Looking at decision-makers operating at different spatial and temporal scales, the analyses of this study introduced a novel approach into the water-use paradigm of rain-fed farming in Argentina. Most studies in the past focused on the amount of water that is needed to produce one kg of product, but few works have paid enough attention to the actual use of rainfall by integrated agricultural systems. The cross-scale analysis in this work demonstrated that properties emerging at one scale do not necessarily maintain its integrity at another scale, and the simple extrapolation of integral units of information across scales may produce misleading results (even opposite results). Notwithstanding the limitations discussed, the framework presented here offers a way to develop a better understanding of the key factors determining water use. As such, it constitutes a first step towards a more integrated knowledge of actual water used in agricultural production in the Pampas.

The water-use issue will inevitably be a focus of attention and concern under a water-scarce scenario, where the competition for water among sectors will increase. Considering the converging dilemmas of water scarcity and the growing global demand for food and fiber, it is likely that the price of agricultural commodities will reflect in the near future the cost of the water used along the production process. Since there is no much room to incorporate irrigation to new lands without depleting the global water resources, which are essential to other uses, rain-fed agriculture will have to receive increasing attention sooner or later.

Acknowledgements

This work was part of F.C. Frank (Degree in Natural Resources, M.Sc.) PhD thesis (Facultad de Ciencias Agrarias – Universidad de Mar del Plata).

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