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Nitrogen-, water- and radiation-use efficiencies affected by sugarcane breeding in Argentina

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With 4 figures and 5 tables

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Abstract

This study aimed to identify whether and how sugarcane (*Saccharum spp.*) breeding in Argentina modified nitrogen-use efficiency (NUE), water-use efficiency (WUE) and radiation-use efficiency (RUE). Thirteen varieties were grown in two consecutive seasons. Trends in different traits were estimated by fitting the data to linear or bilinear regression models. There was a linear increase in NUE and WUE with the year of release throughout the 70-year span, whereas water use was not modified by sugarcane breeding. There was a positive and strong ($r > 0.90$; $P < 0.01$) association between NUE and WUE and between sugar yield and NUE or WUE. Although RUE was not modified by sugarcane breeding, the amount of radiation intercepted by the crop increased with the year of release. Modern varieties had a higher maximum interception and needed fewer days to reach maximum interception than old varieties. This study suggests that applying ecophysiological knowledge would be instrumental in sugarcane breeding programmes in order to develop varieties with high resource-use efficiency and capable to adapt to global climate change.

Key words: ecophysiology — breeding — sugarcane — resource management

Sugarcane (*Saccharum* spp.) crop uses important amounts of carbon inputs to reach maximum yield potential. For example, it ranks second in the rate of fertilizers used for crop production (216 kg/ha) comparing with the mean rate of 109 kg/ha for other crops worldwide (FAO 2006) and consumes 164 l/ha/year of diesel oil during the production process in Argentina (Acreche and Valeiro 2013) compared with consumption ranges from 33 to 48 l/ha/year reported for other crops such as wheat, sunflower, maize and sorghum (Donato 2007). An alternative for reducing the use of carbon inputs in agriculture is to breed new crop varieties with improved resource-use efficiency (Parry and Reynolds 2007) to reach actual yields. For this purpose, it is necessary to complement classical breeding knowledge with techniques generated in other research areas, such as biotechnology or ecophysiology (Parry and Reynolds 2007). Understanding the ecophysiological bases associated with genetic gains can be instrumental at identifying new traits as selection criteria that can maximize yield in crop breeding programmes (Slafer et al. 1994, Reynolds et al. 2001).

In Argentina, sugarcane production area covers 365 000 ha, being concentrated in the north-west region (98%), where it represents the second most important economic and social activity (Wallberg and Minetti 2015). Tucumán is the main sugarcane production province of Argentina, with 68% of total national production (Pérez et al. 2007). All the varieties cultivated in Argentina are selected, bred or introduced by three breeding programmes: 'Obispo Colombres' Experimental Station of Tucuman, 'Chacra Experimental' of Colonia Santa Rosa, Salta, and 'Famaillá' Experimental Station of the National Institute of Agricultural Research, Tucumán, which annually plant 80 000, 200 000 and 25 000 seedlings, respectively. The main breeding goals of these programmes are to increase sugar production (cane yield and sugar content) and reduce the incidence of diseases.

Genetic gains attained in sugarcane breeding in different environments have been frequently reported, with ranges from 0.09 to 0.18 mg of sugar/ha/year (Cook 2001, Wu and Arcinas 2004, Edmé et al. 2005, Jackson 2005, Ming et al. 2006, Cox and Stringer 2007, Fernandez de Ullivarri et al. 2009, Acreche et al. 2015). However, none of those works addressed the changes in resource-use efficiency associated with breeding progress.

Nitrogen (Glass 2003) and water (Parry et al. 2005) are important elements, and their absence can limit crop growth. Therefore, selection for traits related to the efficient use of these inputs should improve crop production or, at least, maintain it reducing the requirement of nitrogen and/or water. Radiation-use efficiency (RUE) can also be a target of breeding programmes, as it is directly related to crop growth and biomass production (Gallagher and Biscoe 1978, Calderini et al. 1997).

Variability in nitrogen-use efficiency (NUE) was reported in a mapping population of sugarcane (Robinson et al. 2007). Singh et al. (2006) also showed variability in water-use efficiency (WUE) when comparing a set of sugarcane varieties. These studies demonstrated that there is considerable genetic variation in NUE and WUE in sugarcane, which can be exploited for breeding purposes.

Very few studies have measured RUE in sugarcane (Sinclair and Muchow 1999), or considered differences between varieties for RUE. One such study by Robertson et al. (1996) showed similar RUE for two Australian varieties ('Q 117' and 'Q 138') with contrasting growth characteristics.

As sugarcane is widely and increasingly demanded for its sugar content (FAO 2010) and its use as biofuel (de Vries et al. 2010), it has a great potential for expansion to cropping areas of low nitrogen and water availability (Carballo et al. 2009). The environmental concerns about the use of high carbon inputs in agriculture show that it is critically important to enhance the current scarce information about new ecophysiological traits that can be exploited by breeding. The main objective of this study was to identify whether and how sugarcane breeding in Argentina has indirectly modified NUE, WUE and RUE in released varieties. To address this objective, representative varieties, released from the 1940s to the beginning of the 21th century, were grown during two consecutive seasons.

Materials and Methods

General: A field experiment was carried out from August 2010 to August 2013 under rain-fed conditions at Famaillá (27°03′ S, 65°25′ W, 363 m a.s.l.) in the Province of Tucumán, the main sugarcane-producing area in Argentina. The experiment was conducted in the experimental fields of the National Institute of Agricultural Research (INTA) during the 2010/11, 2011/12 and 2012/13 growing seasons, corresponding to the plant cane, first ratoon and second ratoon crops, respectively. Only the plant cane and first ratoon crops were analysed in this report.

The soil at the INTA station is classified as Aquic Argiudoll. The presence of a densified layer between 45 and 65 cm limits root development in depth (Tesouro et al. 2011, Fernández de Ullivarri et al. 2014). This hard layer is common in the Tucuman sugarcane fields and has resulted from the extensive use of heavy machinery during the harvest process.

Rainfall from planting to harvest was 1417 mm in the plant cane crop and 992 mm in the first ratoon crop. Soil N-NO_3 contents were 39 and 35 kg/ha in the top 1 m depth after winter for plant cane and first ratoon crops, respectively. Fertilizers were broadcast at tillering at a rate of 110 kg N/ha in the first ratoon crop, whereas no fertilization was applied in the plant cane crop.

Treatments and design: Sugarcane varieties selected, bred or introduced in Argentina were compared because they represent successful breeding achievements. These varieties included a widely grown self-pollinated variety (‘TUC 26-45’), 11 released sugarcane hybrids selected for their success during at least one decade in Tucumán (‘CP 34-120’; ‘NCO 310’; ‘NA 56-79’; ‘CP 48-103’; ‘NA 56-30’; ‘NA 63-90’; ‘CP 65-350’; ‘CP 65-357’; ‘TUCCP 77-42’; ‘LCP 85-384’; ‘RA 87-3’) and an advanced breeding hybrid (‘INTANA 91-209’) from the INTA sugarcane breeding programme that has performed consistently well in several comparative trials. It is important to note that the six foreign varieties were subjected to a selection process at the final stage of the breeding process in Argentina (external comparative trials) before their adoption as commercial varieties (R. Sopena, personal communication). When data were plotted against years of release, it was assumed that INTANA 91-209 was released in 2010, indicating the year this hybrid officially entered the external comparative trials of the breeding programme. Additional details of these varieties are presented in Table 1.

Table 1: Sugarcane varieties grown in Argentina, indicating year of release and period in which the varieties were commercially grown

Variety[1]	Year of release in Argentina	Commercial growth period
TUC 26-45	1940	1940–1960
CP 34-120	1950	1950–1970
NCO 310	1960	1960–present
NA 56-79	1964	1964–present
CP 48-103	1970	1970–1880
NA 56-30	1970	1970–1980
NA 63-90	1977	1977–present
CP 65-350	1987	1987–1990
CP 65-357	1989	1989–present
TUCCP 77-42	1994	1994–present
LCP 85-384	2001	2001–present
RA 87-3	2005	2005–present
INTANA 91-209	–	2015–present

[1]The prefixes of the varieties refer to TUC (crossed and bred in ‘Obispo Colombres’ Experimental Station of Tucumán, Argentina), CP (crossed and bred in Canal Point, USA), NCO (crossed and bred in Natal Coimbatore, South Africa), NA (crossed and bred in ‘Chacra Experimental’ of Colonia Santa Rosa, Salta, Argentina), TUCCP (crossed in Canal Point and bred in Tucumán), LCP (crossed in Canal Point and bred in Louisiana, USA), RA (crossed and bred in República Argentina; a collaborative achievement between breeders of ‘Obispo Colombres’ and ‘Famaillá’ Experimental Station of the National Institute of Agricultural Research, Argentina) and INTANA (crossed in ‘Chacra Experimental’ and bred in ‘Famaillá’ Experimental Station, Argentina).

Treatments were arranged in a randomized complete block design with three replications. Plots, consisting of five 10-m-long rows that were 1.60 m apart, were planted at a density of 15 buds per linear metre, on 24 August 2010.

Weeds and insects were controlled or prevented using recommended products. The ratoon stunting disease (*Leifsonia xyli* subsp. *xyli*) was prevented using seed cane derived from treated nurseries or by treating the seed cane with hydrothermotherapy. The only disease observed in the trial was sugarcane mosaic virus, in varieties ‘CP 65-357’ and ‘CP 34-120’.

Sampling and measurements: Plant samples were taken from all experimental units at ripening. Samples consisted of all plants within one linear metre cut from the three central rows on 30 June 2011 and 02 July 2012 for the plant cane and first ratoon crops, respectively. These dates are around the optimum harvest times for Tucumán. The following parameters were determined in each sample: the number of stalks, average stalk weight, cane yield (CY), sugar recovery and sugar yield (SY) on a fresh-weight basis (Acreche et al. 2015). Samples were oven-dried at 62°C for a week; then, subsamples of 20 stalks were taken from each sample to determine dry weight of leaf blades and stalks (including leaf sheaths). The subsamples were milled and nitrogen content was determined using the Kjeldahl method.

Soil samples to 1 m depth were taken from all experimental units before planting and after each harvest. Samples were taken at four different depths (0–25, 25–50, 50–75 and 75–100 cm). Although sugarcane root extends beyond 4 m below ground (Laclau and Laclau 2009), most of the root biomass is found close to the soil surface and then declines approximately exponentially with depth (Smith et al. 2005). Blackburn (1984) reported that approximately 50% of the sugarcane root biomass occurs in the top 20 cm of soil and 85% in the top 60 cm, which was also confirmed by Evensen et al. (1997).

From each soil sample and depth, a subsample of about 100 g was used to determine water content in the top 1 m by weighing the samples before and after oven drying at 105°C for 48 h. Water use (WU) and water-use efficiency (WUE) were calculated for each variety using Eqns (1) and (2).

$$\begin{aligned} \mathrm{WU\,(mm)} = {} & \text{initial soil water content (mm)} + \\ & \text{effective precipitation during the crop cycle (mm)} - \\ & \text{final soil water content (mm)}. \end{aligned} \quad (1)$$

$$\mathrm{WUE} = \frac{\text{dry stalk weight (kg/ha dry stalk)}}{\mathrm{WU}}. \quad (2)$$

In order to prevent confusing effects of summer excess rain, when monthly effective precipitation was higher than monthly crop evapotranspiration ($ET_{c.}$), the latter was considered effective precipitation. $ET_{c.}$ was estimated as the product of the reference crop evapotranspiration (ET_0) and crop coefficients (K_c). ET_0 was obtained from the meteorological station; Kc (0.4–1.25) depends on the crop growth as indicated by Allen et al. (1998).

The remaining portion of each soil subsample was used to quantify soil mineral N (N-NO_3 content) in the top 1 m of soil using the Nitrachek reflectometer technique (Merckoquant nitrate strips, Merck KGaA, Germany) or with the colorimetric method of Harper. The regression of N content measured with both methods on each other yielded a very high coefficient of determination ($r = 0.95$; $P < 0.001$). Nitrogen-uptake efficiency (NUpE), nitrogen utilization efficiency (NUtE) and nitrogen-use efficiency (NUE) for each variety were calculated (Eqns 3, 4, 5, respectively).

$$\mathrm{NUpE} = \frac{\text{kg N/ha in biomass at maturity}}{\text{N available in soil during the crop cycle}}. \quad (3)$$

$$\text{NUtE} = \frac{\text{dry stalk weight}}{\text{kg N/ha in biomass at maturity}}. \quad (4)$$

$$\text{NUE} = \frac{\text{dry stalk weight}}{\text{N available in the soil}}. \quad (5)$$

The N available in soil during the crop cycle was calculated using Eqn. (6).

$$\text{N available in soil during the crop cycle} = \text{kg N/ha in the soil} + \text{kg N/ha from fertilizers} + \text{mineralized N} \quad (6)$$

The kg N/ha in the soil was measured before planting for plant cane crop and before the harvest of plant cane for ratoon crop.

Mineralized N (78.2 kgN/ha) was estimated following Chalco Vera (2012) using Eqn. (7). This value is within the range of 62–112 kg N/ha, as reported by Ferraris and González Anta (2014) for soybean growing in north-west Argentina.

$$\text{Mineralized N (kg N/ha)} = \text{kg N/ha in biomass at maturity} + \text{kg N/ha in soil at harvest} - \text{kg N/ha in soil at sowing} \quad (7)$$

The loss of N in this environment was considered to be negligible (Portocarrero and Acreche 2014).

During the entire crop cycle, incident and transmitted radiation was weekly measured on clear days at noon using a 1-m-long Linear Ceptometer (Cavadevices, Buenos Aires, Argentina). For this purpose, the line sensor was inserted at ground level across the rows in two different sections of the plots without modifying the canopy architecture. When senescence occurred, the line sensor was placed above senescent leaves. The radiation intercepted by the crop (% IR) was calculated as in Eqn. (8).

$$\%\,\text{IR} = \left(\frac{\text{incident radiation} - \text{transmitted radiation}}{\text{incident radiation}}\right) \times 100. \quad (8)$$

The dynamics of % IR % during the crop cycle was estimated using an optimization procedure based on the trilinear model of Eqn. (9).

$$\text{IR}\,\% = a + b \times \text{DAE} + b \times c + e \times (\text{DAE} - d) \quad (9)$$

The parameter 'a' is the interception at plant emergence; 'b' is the relative change in % IR between 'a' and maximum interception; 'DAE' is days after crop emergence; 'c' is DAE corresponding to the maximum interception; 'd' is DAE at which the maximum interception started to decrease; 'e' is the relative change in % IR between 'd' and ripening. The term '$b \times$ DAE' accounts for DAE equal to or lower than 'c'; '$b \times c$' accounts for DAE higher than 'c'; '$e \times$ (DAE – d)' accounts for DAE equal to or higher than 'd'. All parameters were estimated by the model from actual data.

Incident global radiation was measured at hourly intervals in a meteorological station (Davis Vantage 2) near the experimental site. The amount of radiation intercepted by the crop during the crop cycle (accumulated IR) was calculated as the product of the average % IR of two consecutive samplings and the incident global radiation between them. Then, the IRs calculated for the subperiod were added in order to obtain the accumulated IR during the crop cycle. Radiation-use efficiency (RUE) was calculated as in Eqn. (10).

$$\text{RUE} = \frac{\text{total above-ground dry biomass (kg/m}^2\text{ dry biomass)}}{\text{accumulated IR (MJ/m}^2)}. \quad (10)$$

Data were subjected to an ANOVA. The Fisher's least significant difference (LSD) test was used as criterion for significance of differences among varieties. Trends in different traits were estimated by fitting the data to linear ($Y = a + b \times X$) or bilinear ($Y = a + b \times X + b \times c$) regression models by means of curve-fitting software (Jandell 1991), where 'a' is the intercept, 'b' the slope and 'c' the X value at which maximum Y is reached. Bilinear regressions were not used because they did not perform significantly better than the linear models based on their coefficients of determination. The optimization procedure used for % IR (Eqn. 9) fitted the experimental data iteratively by means of a curve-fitting program (Jandell 1991).

Results

There were significant differences between crops (plant cane and first ratoon) and among varieties for almost all the traits analysed in the study, and their interaction was significant for NUtE, accumulated IR and WU (Table 2). The large crop effect observed for all traits confirms that sugarcane can have very different performance in plant cane crop with respect to ratoon crop (Table 2).

Breeding consistently increased CY and SY with the year of variety release for plant cane and ratoon crops (Table 3). More information can be found in Acreche et al. (2015).

There was not a consistent variation in NUpE between varieties for plant cane crop, whereas for ratoon crop NUpE increased with the year of variety release (Fig. 1a). An effect of breeding on the capacity of the varieties to use the absorbed nitrogen was observed for both plant cane and ratoon crops (Fig. 1b). NUpE increased at the rate of 0.0046 kg N/year in biomass per kg of nitrogen available in the soil for the ratoon crop, whereas NUtE increased at yearly rates of 0.68 and 0.48 kg of dry stalk per kg of nitrogen absorbed for the plant cane and ratoon crops, respectively.

There was a linear increase in NUE with the year of variety release from 1940 to 2010 for plant cane and ratoon crops (Fig. 1c). This result indicates that breeding has consistently modified the capacity of the varieties to use the nitrogen available in the soil, increasing the NUE at yearly rates of 0.44 and 1.06 kg of dry stalk per kg of nitrogen available in the soil for the plant cane and ratoon crops, respectively.

There was a positive and strong association between sugar yield or cane yield and NUE ($r > 0.88$; $P < 0.01$) in plant cane and ratoon crops. NUpE was poorly associated with sugar yield or cane yield in the plant cane crop ($r = 0.58$; $P < 0.05$), whereas it was strongly associated in the ratoon crop ($r > 0.90$; $P < 0.01$). NUtE was associated with sugar yield or cane yield only in the plant cane crop (Table 4).

Water use was not modified by sugarcane breeding in Argentina (Fig. 2a). The difference in the magnitude of mean WU between plant cane (540 mm) and ratoon (410 mm) crops was associated with the effective precipitation during each crop cycle (about 900 and 600 mm for plant cane and ratoon crops, respectively). However, WUE increased with the year of variety release, revealing that breeding modified the capacity of the varieties to use the absorbed water (Fig. 2b). WUE increased at yearly rates of 0.22 and 0.97 kg of dry stalk per mm of water used in varieties grown in the plant cane and ratoon crops, respectively.

There was a positive and strong association between sugar yield or cane yield and WUE ($r > 0.87$; $P < 0.01$) for plant cane and ratoon crops (Table 4), whereas WU was not associated with sugar yield or cane yield ($r < 0.14$; $P > 0.5$) in either crop. WUE was highly associated with NUE ($r = 0.99$; $P < 0.01$) in the plant cane and ratoon crops (Table 4).

The dynamics of % IR with time was estimated using an optimization model that fitted the experimental data to a trilineal model, as illustrated for the variety TUCCP 77-42 in the ratoon

Table 2: Mean squares of nitrogen-uptake efficiency (NUpE), nitrogen utilization efficiency (NUtE), nitrogen-use efficiency (NUE), accumulated intercepted radiation (accumulated IR), radiation-use efficiency (RUE), water use (WU) and water-use efficiency (WUE) for plant cane (2010/11) and ratoon (2011/12) crops

Source of variation	Cane yield	Sugar yield	NUpE	NUtE	NUE	Accumulated IR	RUE	WU	WUE
Crop (C)	18 810***	366***	2.18***	8397***	68 407***	17 496 993***	12.28***	272 243***	106 604***
Variety (V)	2709***	29.9***	0.05*	2848***	1714***	457 364***	0.18	558*	971**
C × V	611	7.36	0.03	2513**	385	118 409***	0.07	669*	406
Error	529	8.04	0.02	669	470	25 834	0.15	279	335

*, **, *** indicate significance at 0.05, 0.01 and 0.001 levels, respectively.

Table 3: Probabilities and differences between means for cane yield (CY) and sugar yield (SY) for sugarcane varieties grown in the plant cane and ratoon crops

Variety	Year of release in Argentina	Plant cane crop CY (Mg/ha)	Plant cane crop SY (Mg/ha)	Ratoon crop CY (Mg/ha)	Ratoon crop SY (Mg/ha)
TUC 26-45	1940	44.57 a	3.38 a	63.73 ab	5.01 ab
CP 34-120	1950	50.76 a	3.51 a	52.20 a	4.03 a
NCO 310	1960	76.05 ab	6.93 ab	80.10 ab	6.81 ab
NA 56-79	1964	64.24 a	5.53 a	115.94 bc	7.44 ab
CP 48-103	1970	90.92 ab	9.20 ab	66.91 ab	6.22 ab
NA 56-30	1970	91.48 ab	8.37 ab	75.94 ab	10.90 bc
NA 63-90	1977	53.54 a	4.94 a	77.09 ab	7.32 ab
CP 65-350	1987	79.42 ab	6.65 a	124.49 bc	10.90 bc
CP 65-357	1989	84.37 ab	8.05 ab	149.50 c	13.21 c
TUCCP 77-42	1994	114.80 b	10.53 b	132.80 bc	11.62 bc
LCP 85-384	2001	82.21 ab	7.86 ab	112.70 bc	11.68 bc
RA 87-3	2005	107.98 b	10.45 b	133.97 bc	13.44 c
INTANA 91-209	–	88.97 ab	8.36 ab	152.47 c	14.59 c
Crops		P < 0.001	P < 0.01	P < 0.001	P < 0.01
Variety		P < 0.001	P < 0.001	P < 0.001	P < 0.001
Crops × Variety		ns	ns	ns	ns

Different letters indicate significance differences among varieties at 0.05 level.

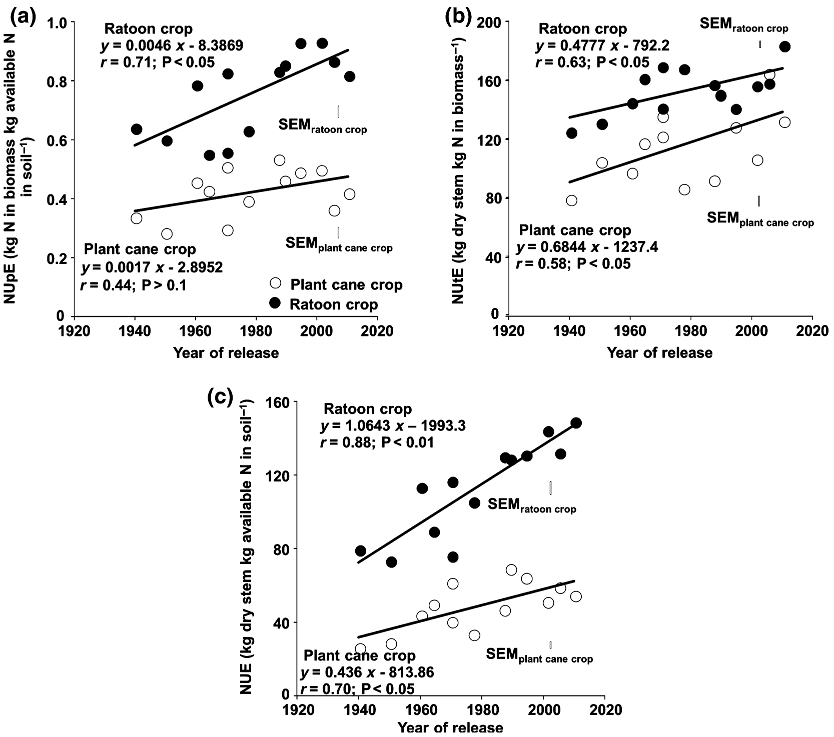

Fig. 1: Trends in nitrogen-uptake efficiency (NUpE, a), nitrogen utilization efficiency (NUtE, b) and nitrogen-use efficiency (NUE, c) with the year of release of sugarcane varieties grown in the plant cane (open symbols) and ratoon (close symbols) crops. SEM stands for standard error of the means for each crop

crop (Fig. 3). In each of the 26 curves analysed in this study (13 varieties and two crops), the model fitted well the data ($r > 0.95$; $P < 0.01$).

Although the duration of the crop cycle was similar among varieties, maximum interception showed significant differences between crops (plant cane and first ratoon), varieties and their interaction, whereas relative change in % IR between plant emergence and maximum interception, and DAE for maximum interception, exhibited differences only among varieties (Table 5). In general, there was a trend to increased maximum interception and relative change in % IR between plant emergence and maximum interception in modern varieties, while they need few days to reach maximum interception (Table 5).

The amount of radiation intercepted by the varieties during each crop cycle increased with the year of release (Fig. 4a), whereas RUE was not consistently modified by sugarcane breeding; however, mean RUE was higher for the varieties released after 1987 than those released before 1987 for the ratoon crop (2.0 vs. 1.76 kg of dry total biomass per MJ intercepted) (Fig. 4b).

Discussion

Although the varieties analysed in this study were not selected directly for higher NUE and WUE, the results presented in this study revealed that over the year of release, sugarcane varieties exhibited a consistent increase in their capacity to generate higher dry stalk per kg of nitrogen available or per mm of water used. These trends were similar to those of CY and SY. The increase in NUE with the year of variety release was associated with (i) a consistent increase in dry stalk weight (see Fig. 3b of Acreche et al. 2015), (ii) an increase in NUpE and (iii) an increase in NUtE. The large difference between plant cane and ratoon crops for NUpE could be associated with two factors: ratoon crop was fertilized with 110 kg N/ha, whereas plant cane crop was not fertilized, as is usual in this sugarcane area, and the crop growth period (first leaf expanded to harvest) was 260 and 300 days for plant cane and ratoon crops, respectively. These factors, and the fact that both NUpE and NUtE increased in ratoon crop and that only NUtE increased in the plant cane crop, led to the difference in NUE between crops.

The high correlation between NUE and sugar yield ($r > 0.91$; $P < 0.01$) and the considerable genetic variation for NUE reported in this study (also stated by Robinson et al. 2007) showed that if breeders include traits related to the efficient use of available nitrogen, important progress could be made in terms of economic results and environment care using varieties that reach high sugar yields with low N inputs. In fact, variety selection is generally conducted with high nitrogen inputs (a common situation in other crops such as *Zea mays* or corn, *Triticum aestivum* or wheat, *Oriza sativa* or rice; see Raun and Jhonson 1999). Presterl et al. (2002) compared European maize hybrids selected under low or high nitrogen inputs and found that the hybrids selected under low N inputs had higher NUE than and similar yield to those hybrids selected under high nitrogen inputs when cultivated under high nitrogen inputs.

There was a parallel increase in NUE and WUE, a situation that is commonly observed in other C4 crops (Eghball and Maranville 1991). The absence of increase in WU reported in this

Table 4: Correlation coefficients between sugar yield, cane yield, nitrogen-uptake efficiency (NUpE), nitrogen utilization efficiency (NUtE), nitrogen-use efficiency (NUE), water use (WU) and water-use efficiency (WUE) for plant cane (2010/11) and ratoon (2011/12) crops

	Sugar yield	Cane yield	NUpE	NUtE	NUE	WU	WUE
Plant cane crop							
Sugar yield	–						
Cane yield	0.98**	–					
NUpE	0.58*	0.58*	–				
NUtE	0.68*	0.67*	0.04	–			
NUE	0.91**	0.88**	0.63*	0.73*	–		
WU	0.04	0.06	0.11	0.07	0.06	–	
WUE	0.90**	0.87**	0.62*	0.74*	0.99**	0.02	–
Ratoon crop							
Sugar yield	–						
Cane yield	0.99**	–					
NUpE	0.90**	0.91**	–				
NUtE	0.30	0.26	0.001	–			
NUE	0.95**	0.94**	0.90**	0.39	–		
WU	0.14	0.12	0.02	0.03	0.10	–	
WUE	0.94**	0.93**	0.89**	0.39	0.99**	0.19	

*, ** indicate significance at 0.05 and 0.01 levels, respectively.

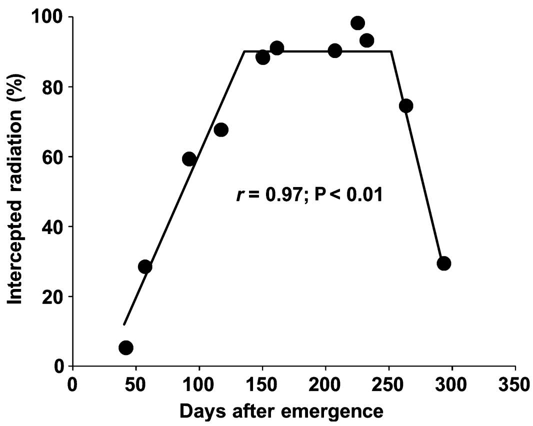

Fig. 3: Adjustment of the percentage of intercepted radiation (%) throughout the crop cycle; the fitting procedure is illustrated for a particular case (variety TUCCP 77-42 in the ratoon crop)

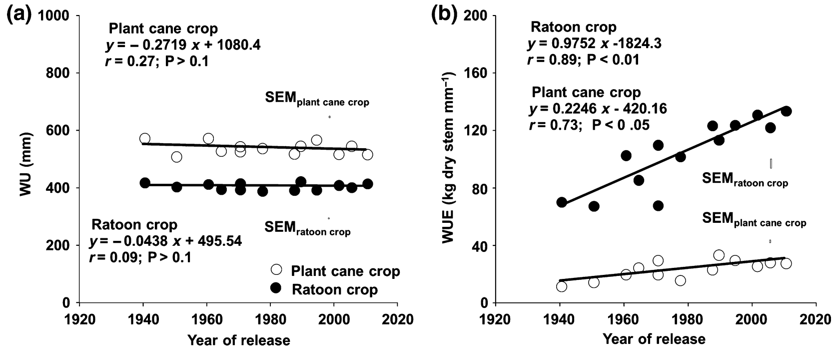

Fig. 2: Trends in water use (WU, a) and water-use efficiency (WUE, b) with the year of release of sugarcane varieties grown in the plant cane (open symbols) and ratoon (close symbols) crops. SEM stands for standard error of the means for each crop

Table 5: Probabilities and differences between means of maximum interception (Mi), relative change in % IR between plant emergence and maximum interception (IRe-mi) and the number of days after emergence to reach maximum interception (days to Mi) for varieties grown in the plant cane and ratoon crops

	Plant cane crop			Ratoon crop		
Variety	Mi	IRe-mi	Days to Mi	Mi	IRe-mi	Days to Mi
TUC 26-45	74.0 bc	0.44 abcd	202 defgh	65.5 a	0.31 a	224 fgh
CP 34-120	70.2 ab	0.40 ab	217 fgh	91.2 ijk	0.46 abcd	226 gh
NCO 310	66.2 ab	0.41 abcd	198 defgh	91.3 ijk	0.38 a	h231
NA 56-79	81.1 cdefg	0.48 abcd	201 defgh	77.0 c	0.48 abcd	178 cde
CP 48-103	80.0 cde	0.57 cdef	159 abcd	86.6 fghi	0.45 abcd	208 efgh
NA 56-30	78.0 cd	0.44 abcd	200 defgh	82.2 cdefg	0.40 abc	202 defgh
NA 63-90	80.7 cdef	0.50 abcde	191 defg	86.4 fghi	0.63 defg	162 abcd
CP 65-350	83.1 defg	0.63 defg	163 abcd	89.3 hijk	0.53 abcde	186 def
CP 65-357	86.8 fghij	0.57 bcdef	179 cdef	90.7 hijk	0.55 abcdef	168 bcd
TUCCP 77-42	90.4 hijk	0.75 fg	135 ab	92.2 jk	0.79 g	135 ab
LCP 85-384	81.6 cdefg	0.51 abcde	178 cdef	93.2 k	0.59 def	165 bcd
RA 87-3	84.8 efgh	0.71 efg	145 abc	89.6 hijk	0.70 efg	147 abc
INTANA 91-209	80.6 cde	0.70 efg	125 a	87.1 ghij	0.63 defg	153 abc
	Mi		IRe-mi		Days to Mi	
Crops	P < 0.001		ns		ns	
Variety	P < 0.001		P < 0.001		P < 0.001	
Crops × Variety	P < 0.001		ns		ns	

Different letters indicate significance differences among varieties at 0.05 level.

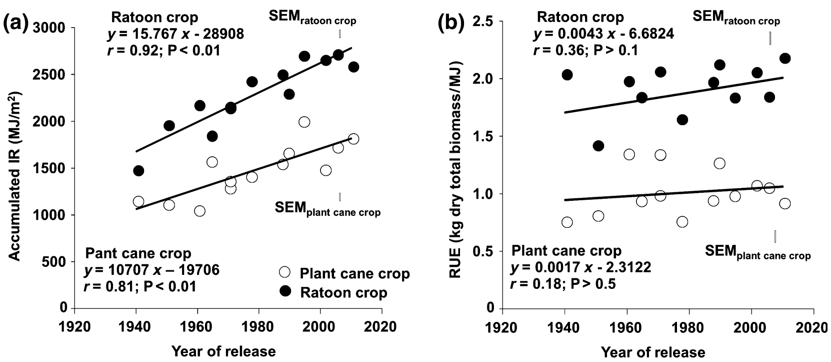

Fig. 4: Trends in accumulated IR during the crop cycle (a) and radiation-use efficiency (RUE, b) with the year of release of sugarcane varieties grown in the plant cane (open symbols) and ratoon (close symbols) crops. SEM stands for standard error of the means for each crop

study revealed that the increment of WUE was associated with the increase in dry stalk weight. In fact, there was a similar increase in WUE to that dry stalk weight (see Fig. 3b of Acreche et al. 2015). WUE was also correlated with sugar and cane yield ($r > 0.87$; $P < 0.01$). Singh et al. (2006) also reported differences in WUE among sugarcane varieties, with no differences in WU among varieties. Similar results were reported by Reyes et al. (2015), who hypothesized that differences in yield of maize hybrids released during the 1963-2009 period in USA would be related to increased WUE rather than increased WU, and by Narayanan et al. (2013) who reported important variability in WUE among sorghum genotypes.

The large difference in WUE between plant cane and ratoon crops could be associated with the following factors: (i) the crop growth period (from first expanded leaf to harvest) was 260 and 300 days for plant cane and ratoon crops, respectively, generating much higher dry stalk weight in ratoon crop than in plant cane crop (Acreche et al. 2015), and (ii) effective precipitation was higher during the 2010/11 cycle (plant cane; 900 mm) than during the 2011/12 cycle (ratoon crop; 600 mm), generating higher WU in plant cane crop (540 mm) than in ratoon crop (410 mm).

It is well documented that increasing WU leads to increments in total biomass under drought-prone environments (Blum 2005). This phenomenon, and the facts that most of the sugarcane of Argentina is cultivated without irrigation, and the potential expansion of this crop to cropping areas of low water availability (Carballo et al. 2009) show the need to enhance the scarce improvement in WU; however, such strategy could be difficult to attain. To obtain an increase in biomass, Passioura (2004) proposed higher capture of water supply for use in transpiration and a best exchange of transpired water for CO_2. In fact, Blum (2009) proposed the effective use of water (maximizing soil water capture while diverting the largest part of the available soil moisture towards stomatal transpiration) as a target for improving yield under drought environments. Increasing WU would be instrumental for future sugarcane farmers, because global climate change will impact agricultural production through increasing temperatures or with more erratic rainfall (Parry et al. 2005).

In the present study, the dynamics of % IR in each crop cycle was different among varieties. The different dynamics of % IR and the fact that the crop cycle duration was similar among varieties indicated that the amount of radiation intercepted by the crop increased with the year of variety release. RUE did not change with the year of release, which is in agreement with findings reported by Robertson et al. (1996) for two sugarcane varieties of contrasting growth characteristics. However, the mean RUE of varieties released after 1987 was slightly higher

(0.24 kg of dry total biomass per MJ intercepted) than that of the varieties released before 1987 in the ratoon crop. These results differ from those reported by Narayanan et al. (2013), who showed differences among sorghum genotypes for RUE.

As total above-ground biomass increased with the year of release of the varieties (Acreche et al. 2015), the lack of a consistent increase in RUE with the year of release could be associated with an already high RUE of old varieties (sugarcane is one of the most efficient crops producing biomass per amount of radiation use; Sinclair and Muchow 1999) or an inefficient use of the intercepted radiation at physiological level of modern varieties.

The results suggest the difficulties in modifying the efficient use of intercepted radiation at the physiological level. Therefore, narrowing row spacing to make the use of soil area more efficient could be an alternative strategy to increase the amount of radiation intercepted by the crop at the area level and, therefore, the total above-ground biomass per area while maintaining the high RUE. In fact, sugarcane has been traditionally grown in Argentina since 1961 with a row spacing of 1.6 m (Fogliata 1995). A reduction in row spacing has increased yields in corn (Maizar 2013), soybean (Baigorri and Croatto 2000) and cotton (Mondino 2000).

The dynamics of % IR found in this study was associated with different architectural properties of the canopy responsible for the interception of incoming radiation: modern varieties, which had a higher maximum interception and needed a few days to reach maximum interception, had more semi-erectile or erectile leaf architecture than old varieties. In fact, Irvine and Brenda (1980) and Galvani et al. (1997) suggested a best radiation profit for sugarcane varieties with more erectile leaves growing in narrow rows.

Thus, sugarcane breeders in Argentina should select varieties adapted to narrower row spacing to take better advantage of the incoming radiation. Accordingly, Ahmed and Mariotti (1988) demonstrated that selecting sugarcane under different row spacing modified the variety characteristics and the expression of yield components. This strategy could also increase WU due to low soil evaporation in the beginning of the sugarcane cycle.

This study suggests that applying ecophysiological knowledge would be instrumental in sugarcane breeding programmes in order to develop varieties with high resource-use efficiency and capable to adapt to global climate change.

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