Field Crops Research 149 (2013) 300–311

Contents lists available at SciVerse ScienceDirect

Field Crops Research

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

Modelling long-term effects of cropping intensification reveals increased water and radiation productivity in the South-eastern Pampas

O.P. Caviglia[a,*], V.O. Sadras[b], F.H. Andrade[c]

[a] INTA EEA Paraná – FCA (UNER), Ruta 11, km 12.5, 3100 Paraná, Argentina
[b] South Australian Research and Development Institute, The University of Adelaide, Waite Campus, Adelaide, SA 5001, Australia
[c] INTA – Universidad de Mar del Plata, Balcarce, Argentina

ARTICLE INFO

Article history:
Received 6 January 2012
Received in revised form 11 April 2013
Accepted 1 May 2013

Keywords:
Double crop
Water use efficiency
Soybean
Wheat
Maize

ABSTRACT

Wheat/soybean double crop provides a reliable platform for cropping intensification in many subtropical and temperate areas, even in those with a short growing season as the South-eastern Pampas of Argentina. However, the long-term impact of double cropping as part of feasible cropping sequences on resource productivity and the whole sequence performance is unknown. We propose that cropping intensification, based on wheat/soybean double cropping would (i) improve the annual water and radiation capture and productivity, and (ii) reduce unproductive water losses estimated on an annual basis. We tested these hypotheses through long term simulations (30 years), using DSSAT models locally calibrated and tested for wheat (W) (*Triticum aestivum* L.), soybean (S) (*Glycine max* [L.] Merr.) and maize (M) (*Zea mays* L.). Intensification was quantified with the index ISI = number of crops in rotation/duration of rotation. Pairs of sequences with similar crop composition but different degree of intensification were compared, i.e. W–S ($\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$) vs W/S double crop ($\mathrm{ISI} = 2\,\mathrm{yr}^{-1}$), W–S–M ($\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$) vs W/S–M ($\mathrm{ISI} = 1.5\,\mathrm{yr}^{-1}$) and W–S–M–S ($\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$) vs W/S–M–S ($\mathrm{ISI} = 1.33\,\mathrm{yr}^{-1}$). The study also included feasible or traditional rotations of our region. The increase in intensification improved annual resource capture and therefore water and radiation productivity. Proportion of maize in sequences, irrespective of ISI, additionally increased resource productivity by increasing both water use efficiency (WUE) and radiation use efficiency (RUE). Across sequences, WUE and RUE were strongly associated. This correlation was involved in the link between water and radiation productivity. The increase in water productivity was related ($P < 0.0001$) to a reduction in water loss, mainly accounted by runoff. In the long term, sequences with high intensification ($\mathrm{ISI} \geq 1.5\,\mathrm{yr}^{-1}$) had as high stability and productivity as traditional sequences of our region, based on wheat-summer crop with $\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$. Overall, wheat conferred stability to the sequences whereas maize conferred productivity. Our study, accounting for the ability of whole cropping systems to capture resources on an annual basis, gives new tools to develop more efficient and sustainable cropping sequences.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

South America, chiefly Brazil and Argentina, currently accounts for 43% of worldwide soybean production (FAO, 2011). The growth in soybean acreage over the last decades contributed to both a progressive simplification in local agroecosystems and the advance of agriculture onto new cropped areas, which are often environmentally more fragile and less productive than typical agricultural land (Calviño and Monzon, 2009). Although the trade benefits of soybean are critical for the income of many South American countries, the encroachment of soybean-based systems in vulnerable tropical, subtropical and temperate regions has raised strong environmental and social concerns. For example, nutrient mining and low return of harvest residues in soybean-dominated cropping systems may

---

Abbreviations: LER, land equivalence ratio; ISI, intensification sequence index; MP, maize proportion; $\mathrm{WP_{DM}}$, water productivity for dry matter; $\mathrm{WP_{Y}}$, water productivity for grain yield; C_{WATER}, water capture efficiency; C_{RAD}, radiation capture efficiency; $\mathrm{WUE_{DM}}$, water use efficiency for dry matter; $\mathrm{WUE_{Y}}$, water use efficiency for grain yield; $\mathrm{RP_{DM}}$, radiation productivity for dry matter; $\mathrm{RP_{Y}}$, radiation productivity for grain yield; PAR, photosynthetically active radiation; IPAR, cumulative PAR intercepted by crops; $\mathrm{RUE_{DM}}$, radiation use efficiency for dry matter; $\mathrm{RUE_{Y}}$, radiation use efficiency for grain yield; ET, evapotranspiration.

[*] Corresponding author. Tel.: +54 343 4975200; fax: +54 343 4975200.
E-mail address: ocaviglia@parana.inta.gov.ar (O.P. Caviglia).

0378-4290/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fcr.2013.05.003

impair soil structure and fertility in the long-term (Studdert and Echeverria, 2000; Caviglia and Andrade, 2010; Novelli et al., 2011).

Cropping systems based on a single crop per year capture only a fraction of the annual offer of resources such as water and solar radiation, wasting a considerable fraction of potential productivity (Caviglia et al., 2004). Thus, cropping intensification is critical to meet the future human needs for food and fibre. Such intensification involves two elements: increase of cropping intensity, i.e. more crops per unit area and time (Evans, 1993, 2003; Sadras et al., 2009; Caviglia and Andrade, 2010) and better management of inputs in individual crops (Cassman et al., 2003; Calviño and Monzon, 2009).

The most reliable alternative for the intensification of cropping systems in many temperate areas involves wheat/soybean double cropping, even in regions with a short growing season as the South-eastern Pampas (Calviño et al., 2003a; Caviglia et al., 2004; Calviño and Monzon, 2009). Factors that make double cropping a technically feasible, highly profitable option in this region relate to the skills that local growers have developed from growing individual wheat and soybean crops and a combination of favourable prices and technology factors including transgenic soybeans and no-till (Calviño and Monzon, 2009; Caviglia et al., 2011).

Wheat/soybean double crops improved annual water- and radiation-productivity in comparison to individual crops in the South-eastern Pampas (Caviglia et al., 2004). The increased resource productivity was reached through a greater capture of resources, rather than improved resource use efficiency. In this system, land equivalence ratio (LER, land required for individual crops to produce the same amount of each crop component as that obtained with the double crop) of wheat–soybean double crops can be as high as 1.9 (Caviglia et al., 2011), suggesting that one area unit of double crop may be as productive as almost two area units of the individual crops. As in the most of temperate agricultural systems, the widespread cropping sequence in our region traditionally included a single crop per year including wheat in a year and a summer crops such as maize, soybean and sunflower in the next year. Lately, however, the cropped area with soybean mainly as a single crop per year has notably increased, whereas a considerable area of wheat has been replaced with barley (*Hordeum vulgare* L.).

Crop sequences have been widely studied, particularly in arid and semi-arid regions, focusing on residual water and nutrients (Nielsen, 1998; Halvorson et al., 1999; Aase and Pikul, 2000; Nielsen et al., 2002; Smith et al., 2008). Consequences of cropping sequences on water use efficiency have also received considerable attention (Hergert et al., 1993; Norwood, 1994; Jones and Popham, 1997; Huang et al., 2003; Sadras et al., 2004; Nielsen et al., 2011). There are no reports, however, on the effect that wheat/soybean double cropping, integrated in technologically feasible rotations in humid or sub-humid areas, could have on capture and efficiency in the use water and radiation. Moreover, studies on crop rotations considering the linkages between water and radiation are lacking.

Improving the capture of water and radiation not only increases productivity and whole system efficiency; it may also positively contribute to the reduction of environmental problems. In fact, increasing the capture of solar radiation by crops may increase the return of vegetal material to the system, which may improve soil conditions (Shaver et al., 2003) including soil carbon balance (Studdert and Echeverria, 2000), nutrient cycling (Reeves, 1997) and soil aggregation (Tisdall and Oades, 1982; Wright and Hons, 2004; Novelli et al., 2011). The relationship between annual rainfall and evapotranspiration (ET) in grassed and forest agroecosystems is non-linear, reflecting a rising "excess water" component (mainly accounted by runoff and deep drainage) with increasing annual rainfall (Zhang et al., 2001). Therefore, in humid or sub-humid regions, intensification through higher cropping intensity may increase capture of water by crops, reduce the "excess water" and reduce the risk of soil erosion (Nosetto et al., 2005, 2012), leaching of nutrients and pesticides (Sadras and Roget, 2004; Díaz-Ambrona et al., 2005; Portela et al., 2009; Montoya et al., 2006) and dryland salinization associated with rising water tables (McFarlane et al., 1992; Nosetto et al., 2008, 2009; Díaz-Ambrona et al., 2005).

The aim of this paper was to evaluate the long term effect of cropping intensification on resource capture and productivity using crop simulation DSSAT models. Cropping sequences involving common or feasible single crop per year sequences in the region are compared with sequences including wheat/soybean double cropping. Our working hypotheses are that (i) intensification based on wheat/soybean double cropping leads to a long-term improvement in annual water and radiation capture and productivity, and (ii) improved water productivity is associated with reductions in unproductive water losses assessed on an annual basis.

2. Methods

2.1. Crop sequences

Three pairs of crop sequences were designed that had similar crop composition but different degree of intensification through the inclusion of wheat/soybean double crop (sequences 1–6, Table 1). We also evaluated four crop sequences which are common or feasible in the region (sequences 7–10, Table 1). Two indices were used to characterize crop sequences: the intensification sequence index (ISI), calculated as the ratio between the number of crops and the duration of a given sequence (Farahani et al., 1998), and the maize proportion (MP), calculated as the ratio of number of maize crops in the sequence and crop sequence duration (Table 1).

2.2. Model evaluation

Our cropping sequences involved different combinations of wheat, maize and soybean (Table 1). We therefore evaluated the ability of the models CERES-Wheat (Ritchie and Otter, 1985), CERES-Maize (Jones and Kiniry, 1986) and CROPGRO-Soybean (Hoogenboon et al., 1994) of DSSAT (v.3.5) (Hoogenboon et al., 1999) to estimate: (i) yield and timing of key phenological stages for all three crops and, (ii) evapotranspiration (ET) and photosynthetically active radiation (PAR) interception of wheat/soybean double crop using the SEQUENCE mode of DSSAT (Thornton et al., 1995).

Phenological scales were Zadoks et al. (1974) for wheat, Fehr and Caviness (1977) for soybean, and Ritchie and Hanway (1982) for maize. Genetic coefficients for soybean A3901 (maturity group III, glyphosate resistant), spring wheat PROINTA Imperial, and maize

Table 1
Crop sequence composition, duration, intensification sequence index (ISI), and maize proportion (MP) simulated in Balcarce, Argentina. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

Sequence	Number of crops	Duration[a] (year)	ISI[b] (yr^{-1})	MP[c] (yr^{-1})
(1) W/S	2	1	2	0
(2) W–S	2	2	1	0
(3) W/S–M	3	2	1.5	0.5
(4) W–S–M	3	3	1	0.33
(5) W/S–M–S	4	3	1.33	0.33
(6) W–S–M–S	4	4	1	0.25
(7) W–S–W–M	4	4	1	0.25
(8) W–M	2	2	1	0.5
(9) S–M	2	2	1	0.5
(10) W/S–S	3	2	1.5	0

[a] Duration of sequences was evaluated computing each year from 1 May to 30 April.

[b] The intensification sequence index (Farahani et al., 1998) is the ratio between the number of crops in the sequence and its duration in years.

[c] Maize proportion is the ratio of number of maize crops in the sequence and crop sequence duration.

Dekalb 636 were obtained using GENCALC procedures developed for DSSAT (v.3.5) models (Hunt et al., 1993; Hoogenboon et al., 1999). Data to obtain genetic coefficients for wheat and soybean were obtained from variety trials at two locations in the region (Bariffi, H. and Gutheim, F., unpublished). Data for maize were obtained from local experiments reported by Cirilo and Andrade (1994).

Simulations were contrasted with measurements from independent experiments including (i) wheat and soybean yield and phenology from variety trials at two locations in the region, (ii) wheat/soybean components of water budget and dynamics of PAR interception and growth (Caviglia et al., 2004), and (iii) maize phenology and yield (Cirilo and Andrade, 1994; Barbieri et al., 2000; Sainz Rosas et al., 2000).

The components of water budget used for validation were estimated using a water balance based on twice weekly measurements of soil water content and effective rainfall, whereas the data of the dynamics of PAR interception by crops for validation were based on frequent measurements using a lineal quantum sensor (for further details see Caviglia et al., 2004).

Simulated and measured data were compared using Modell II lineal regression (Fila et al., 2003) to account for bias associated with the definition of independent variable, i.e. observed (y) vs estimated (x) or estimated (y) vs observed (x) (Piñeiro et al., 2008) slope and intercept of regression were calculated using PROC REG of SAS package (SAS, 2003). The mean square error (MSE) was partitioned in bias (SB) and mean square of variation (MSV) using IRENE software (Fila et al., 2003). Bias (SB) is an integrative index of deviation of simulated values from observed ones. A higher MSV indicate that model has no ability to simulate the variability around average. Bias and MSV are orthogonal and, in consequence, can be analysed independently (Kobayashi and Us Salam, 2000).

2.3. Simulation of crop sequences: resource productivity and annual yield per unit area

The SEQUENCE mode of DSSAT was used to carry over soil water content thorough the crops in the sequence (Thornton et al., 1995; Hoogenboon et al., 1999). No attempt was made to account for nutrient deficiencies, weeds, diseases or insect pests. Each sequence in Table 1, and continuous soybean, maize and wheat were simulated for 30 consecutive years using historical weather records of Balcarce (37.5° S; 58.2° W; 130 m.a.s.l.). Two or three sets of simulations were run for sequences in order to include each single crop in all years of historical weather records, e.g. sequence W/S–M was run in two sets starting in 1971 and 1972, as a result wheat/soybean double crop or maize crop were simulated in every single year of historical records. The simulated soil was a fine, mixed, thermic Typic Argiudoll, which was similar to the soil in the experimental sites used for validation (Section 2.2). The initial soil water content at the onset of simulation was set at 50% of available water. Total available water for the simulated soil was 200 mm up to 1.6-m depth. The main soils in our region are Typic Argiudolls, Typic Haplustolls and Petrocalcic Paleustolls, although the main source of variation in maximum soil available water is the variation in soil depth due to the presence of a pretrocalcic horizon.

Sowing date was set automatically when soil water content was higher than 50% of field capacity and temperature was higher than 5 (wheat) or 10 °C (soybean and maize), in a window from 20 July to 15 August for wheat, from 10 October to 15 November for maize, from 10 November to 15 December for soybean as sole crop and from 20 December to 20 January for sequential double cropped soybean, after wheat harvest.

2.3.1. Calculations and indices

Average grain yield of sequences was compared with yield estimated as a function of simulated yield of continuous crops, i.e. the ratio between the sum of continuous crop yield and duration of sequence in years. Continuous crop refers to continuous wheat, soybean or maize with an ISI = 1 yr^{-1}. When a sequence had wheat/soybean double crop, the average of the continuous crop yields was used. For example, for W/S–M sequence average grain yield as a function of continuous crops was estimated as:

$$\text{Average yield as a function of continuous crops yield} = \frac{[(W_{\mathrm{cc}} + S_{\mathrm{cc}})/2] + M_{\mathrm{cc}}}{d} \quad (1)$$

where suffix cc indicate average simulated grain yield of continuous crop (W: wheat; S: soybean and M: maize); d is the duration of the sequence in years. The sequence of the example had 2 years of duration.

The difference between simulated sequence yield and yield estimated as a function of continuous crops yield (Eq. (1)) is a useful indicator of the advantages of sequences. The increase in simulated yield of sequences in relation to the estimated yield as a function of simulated continuous crop yield was regressed against ISI. Simulated grain yield was expressed, also, as glucose yield based on our own results (Caviglia et al., 2004, 2011) or literature values (Penning de Vries, 1972); production values used for calculations were 0.45, 0.36 and 0.86 g product $(\mathrm{g\ glucose})^{-1}$ for protein, lipids and carbohydrates (Penning de Vries, 1972) yielding in average 0.81, 0.77 and 0.57 g grain $(\mathrm{g\ glucose})^{-1}$ for maize, wheat and soybean, respectively.

Water productivity (i.e. $\mathrm{WP_{DM}}$ = shoot dry matter per unit annual rainfall) was analysed as the product of capture and efficiency factors on an annual basis i.e. from 1 May to 30 April.

$$\mathrm{WP_{DM}} = C_{\mathrm{WATER}} \times \mathrm{WUE_{DM}} \quad (2)$$

where C_{WATER} is the capture efficiency and $\mathrm{WUE_{DM}}$ is water use efficiency for shoot dry mater. Similarly, we defined radiation productivity (RP) as:

$$\mathrm{RP_{DM}} = C_{\mathrm{RAD}} \times \mathrm{RUE_{DM}} \quad (3)$$

where C_{RAD} is the capture efficiency and $\mathrm{RUE_{DM}}$ is the radiation use efficiency for shoot dry matter. Eqs. (2) and (3) were also used to evaluate resource productivity on a grain yield (Y) basis ($\mathrm{WP_Y}$ and $\mathrm{RP_Y}$).

Water capture efficiency (C_{WATER}) was calculated as the ratio between the sum of ET of each crop component of a given sequence and total rainfall during the cropping sequence. Radiation capture was calculated as the ratio between total amount of PAR intercepted by crops and incident PAR during the whole sequence (C_{RAD}). Daily PAR interception was calculated using Lambert–Beer's law with simulated values of LAI and coefficients of extinction of 0.65, 0.85 and 0.67 for wheat, soybean and maize, respectively.

Water use efficiency (WUE) was calculated as the ratio between the sum of grain yield ($\mathrm{WUE_Y}$) or shoot dry matter ($\mathrm{WUE_{DM}}$) and the sum of ET of crops. Radiation use efficiency (RUE) was estimated as the ratio of the sum of grain yield ($\mathrm{RUE_Y}$) or dry matter ($\mathrm{RUE_{DM}}$) and the sum of IPAR of crops. Fractional water loss to pathways other than ET (excess water) was calculated as the proportion of rainfall and soil available water that was not lost by evapotranspiration by crops, i.e. ((rainfall + soil available water) – ET)/(rainfall + soil available water); this value is associated with $1 - C_{\mathrm{WATER}}$.

Frequency histograms were used to build-up cumulative frequency of annual grain yield or glucose yield of crop sequences. For a given crop sequence, the effect of intensification was tested using Tukey test whenever ANOVA was significant ($P < 0.05$). Association among variables was evaluated using correlation analysis, multiple and lineal regression through procedures included in SAS package (SAS, 2003).

3. Results

3.1. Model evaluation

Table 2 summarizes the relationships between simulated and observed phenology dates and yield for all three crops. Estimates of key phenological stages were reasonable for all three crops, particularly for wheat. For maize and soybean, increasing RMSE for successive phenological stages may have resulted from compounded errors through development. Yield estimates were reasonable for all crops. In fact, the bias (SB) accounted for less than 21% of mean square error (MSE) for yield in wheat, maize and soybean.

Cumulative intercepted PAR and ET were acceptably simulated for double cropped wheat/soybean (Fig. 1), even though no double cropped soybean data were used to adjust genetic coefficients. There was a close agreement between simulated and measured total amount of total intercepted IPAR ($P < 0.02$, $R^2 = 0.97$) or ET ($P < 0.04$; $R^2 = 0.92$) as well as between simulated and measured fractional PAR interception ($P < 0.0001$, $R^2 = 0.72$). The models also generated reasonable estimates of shoot dry matter ($P < 0.01$, $R^2 = 0.72$).

3.2. Simulation of crop sequences differing in degree of intensification

3.2.1. Yield per unit area and year

For each crop sequence pair, intensification increased shoot dry matter, grain yield and crop harvest residues (Table 3). Percentage of yield increase in sequence with higher ISI in relation to their respective counterpart was proportional to ISI increase ($P < 0.0001$). Neither MP nor ISI accounted for annual yield variation of pooled data including all crop sequences, but both indexes together (included in a multiple linear model) accounted for 89% of annual yield variation ($P < 0.02$), and for 90% of total dry matter production.

3.2.2. Resource productivity: water and radiation

Table 4 summarizes the effects of intensification and crop composition on radiation productivity and its components. Intensification increased the amount of annual intercepted PAR by more than 35% with $\mathrm{ISI} \geq 1.5\,\mathrm{yr}^{-1}$, and by 10% with $\mathrm{ISI} = 1.33\,\mathrm{yr}^{-1}$. The presence of maize in sequences with $\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$ favoured interception of PAR. Annual C_{RAD} increased from 0.27–0.31 for $\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$ to 0.35–0.42 for $\mathrm{ISI} > 1\,\mathrm{yr}^{-1}$. Intensification did not affect radiation use efficiency ($\mathrm{RUE_Y}$ and $\mathrm{RUE_{DM}}$), which was slightly greater in sequences that included maize. In contrast, annual radiation productivity increased proportionally to ISI, i.e. in relation to a single crop per year ($\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$), $\mathrm{RP_Y}$ and $\mathrm{RP_{DM}}$ increased 14–15% with $\mathrm{ISI} = 1.33\,\mathrm{yr}^{-1}$, 21–25% with $\mathrm{ISI} = 1.5\,\mathrm{yr}^{-1}$ and 37–40% with $\mathrm{ISI} = 2\,\mathrm{yr}^{-1}$.

Table 5 summarizes the effects of intensification and crop composition on water productivity and its components. Annual evapotranspiration in sequences involving a single crop per year ($\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$) averaged 444 mm, and was unaffected by crop composition. Intensification increased annual ET; the increase in intensified sequences as compared with their respective counterpart with $\mathrm{ISI} = 1\,\mathrm{yr}^{-1}$ was proportional to ISI, i.e. it was 15% with $\mathrm{ISI} = 1.33\,\mathrm{yr}^{-1}$, 22% with $\mathrm{ISI} = 1.5\,\mathrm{yr}^{-1}$ and, 43% with $\mathrm{ISI} = 2\,\mathrm{yr}^{-1}$. As a result, intensification increased annual capture of water (C_{WATER}). Intensification did not affect water use efficiency ($\mathrm{WUE_Y}$ and $\mathrm{WUE_{DM}}$). The proportion of maize in the sequence accounted for 71% ($P < 0.04$) of the variation in $\mathrm{WUE_Y}$ and 75% of the variation in $\mathrm{WUE_{DM}}$ ($P < 0.03$). Increase in ISI lead to a proportional increase in annual water productivity, i.e. $\mathrm{WP_Y}$ and $\mathrm{WP_{DM}}$ raised 13–15%,

Table 2

Coefficients of linear regression between observed and simulated values, root mean square error (RMSE), mean square error (MSE) partitioning in bias (SB) and mean square variation (MSV) for yield and crop phenology dates of wheat, soybean and maize. *n*: number of crops used for validation.

Crop	Variable	*n*	Linear regression			RMSE	Error components (% of MSE)	
			R^2	Intercept ± SE	Slope ± SE		SB	MSV
Wheat	Yield ($\mathrm{kg\,ha^{-1}}$)	15	0.79	−619ns ± 625	1.05^{**} ± 0.11	748	18	82
	Anthesis (d)		0.82	59ns ± 57	0.82^{**} ± 0.19	4.7	17	83
	Maturity (d)		0.57	−55ns ± 126	1.16^{*} ± 0.36	3.6	1	99
Soybean	Yield ($\mathrm{kg\,ha^{-1}}$)	14	0.55	539ns ± 644	0.83^{**} ± 0.22	573	0	100
	R1 (d)		0.96	−1.6ns ± 1.6	0.91^{**} ± 0.06	4.7	31	69
	R3 (d)		0.90	8.1^{*} ± 3.0	0.68^{**} ± 0.07	7.2	27	73
	R5 (d)		0.86	14.5^{**} ± 3.5	0.60^{**} ± 0.07	8.0	38	62
	Maturity (d)		0.91	22.1^{**} ± 5.4	0.64^{**} ± 0.06	12.6	19	81
Maize	Yield ($\mathrm{kg\,ha^{-1}}$)	14	0.75	2744^{*} ± 1417	0.71^{**} ± 0.12	1582	21	79
	R1 (d)		0.99	−2.4ns ± 1.7	0.98^{**} ± 0.008	6.5	53	47
	Maturity (d)		0.91	44.4^{*} ± 14.5	1.47^{**} ± 0.16	14.3	4	96

SE: standard error.

* $P < 0.05$.

** $P < 0.01$.

Table 3

Annual grain yield, annual dry matter and annual crop residue input in crop sequences varying in intensification level. Simulated results using a 30 years series of historical weather records of Balcarce, Argentina. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

	Sequence					
	W/S ISI	W–S	W/S–M ISI	W–S–M	W/S–M–S ISI	W–S–M–S
	2	1	1.5	1	1.33	1
Grain yield, $\mathrm{kg\,ha^{-1}\,yr^{-1}}$	5241*a*	3879b	6158*a*	5138b	5030*a*	4460b
Dry matter, $\mathrm{kg\,ha^{-1}\,yr^{-1}}$	12149*a*	8745b	14390*a*	11603b	11492*a*	10058b
Harvest residues, $\mathrm{kg\,ha^{-1}\,yr^{-1}}$	6908*a*	4866b	8233*a*	6465b	6461*a*	5598b

Means followed by the same letter within an ISI level are not significantly different. Tukey ($\alpha = 0.05$).

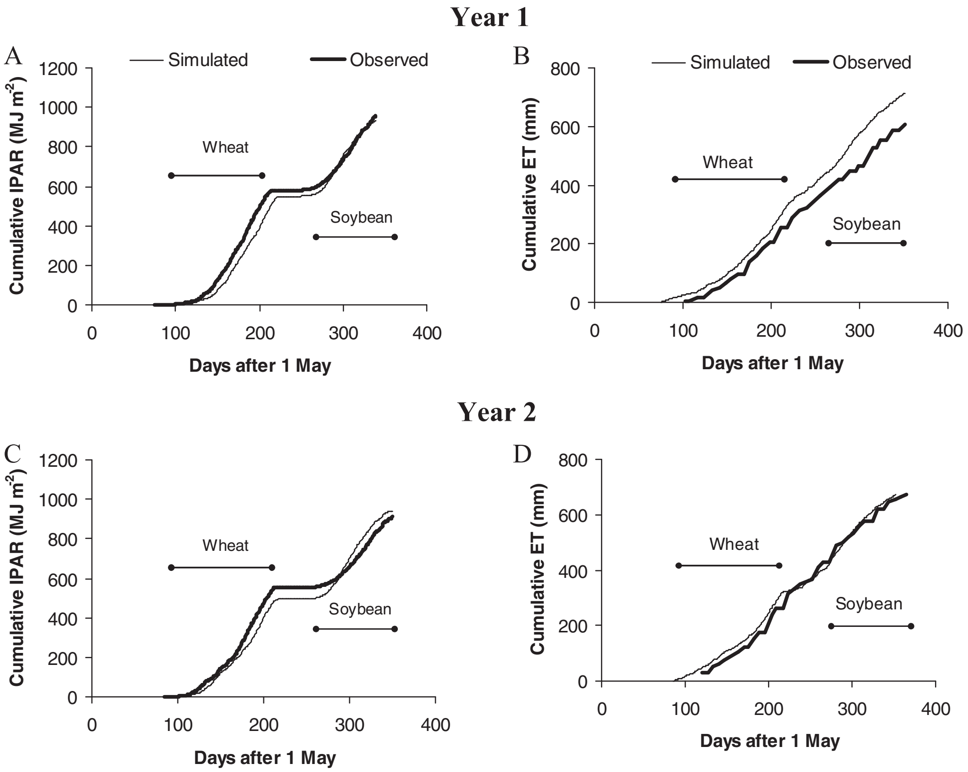

Fig. 1. Simulated and observed cumulative intercepted photosynthetically active radiation (PAR) (A) and (C) and cumulative evapotranspiration (B) and (D) of wheat/soybean sequential double crop in two years at Balcarce, Argentina. Simulation performed using sequential mode of DSSAT, i.e. final conditions of wheat crop are transferred to the sequential soybean crop.

19–23% and 37–41%with ISI 1.33 yr^{-1}, 1.5 yr^{-1} and 2 yr^{-1}, respectively.

3.2.3. Links between components of resource productivity

Fig. 2 summarizes the links among resource productivities and their components. Annual resource productivities for grain yield (RP_Y and WP_Y) were more closely related to resource use efficiency than to capture of water and radiation. Water and radiation productivity (WP and RP) were strongly related. Likewise, there was a strong coupling between radiation- and water-use efficiencies. Water and radiation productivities for yield (WP_Y and RP_Y) were strongly associated with the productivities for dry matter production (WP_{DM} and RP_{DM}) ($r > 0.94$, $P < 0.0001$).

Not surprisingly, annual grain yield per unit area was closely related to annual resource productivity ($r = 0.90$, $P < 0.0001$ for WP_Y; $r = 0.95$, $P < 0.0001$ for RP_Y). Similarly, strong associations were found between total dry matter production and resource productivity for dry matter ($r = 0.87$, $P < 0.0001$ for WP_{DM}; and $r = 0.94$, $P < 0.0001$ for RP_{DM}).

Annual water productivity for yield (WP_Y) was more strongly related to WUE_Y than to C_{WATER}. However, WUE_Y was only affected by sequence composition (MP) whereas C_{WATER} was affected by ISI. Therefore, increases in WP_Y by intensification should be attributable to an enhanced water capture. Moreover, excess water accounted for 66–68% of the variation in WP (Fig. 3).

In-season runoff probabilities decreased as ISI increased (Fig. 4). The lower the differences in ISI within a pair sequence the lower the differences in in-season runoff.

Crop ET was consistently higher in systems with higher ISI (Table 5 and Fig. 5). For example, ET accounted in average for 66%

Table 4
Radiation productivity and its components in crop sequences varying in intensification simulated using a 30 years series of historical weather records of Balcarce, Argentina. RUE_{DM}: radiation use efficiency for dry matter; RUE_Y: radiation use efficiency for grain yield; RP_{DM}: radiation productivity for dry matter; RP_Y: radiation productivity for grain yield; IPAR: cumulative PAR intercepted by the crop; C_{RAD}: radiation capture efficiency. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

Variable	Sequence					
	W/S	W–S	W/S–M	W–S–M	W/S–M–S	W–S–M–S
	(2)[a] [0][b]	(1) [0]	(1.5) [0.5]	(1) [0.33]	(1.33) [0.33]	(1) [0.25]
Annual IPAR (MJ yr^{-1})	956a	696b	1069a	766b	878a	797b
C_{RAD}	0.38a	0.27b	0.42a	0.30b	0.35a	0.31b
RUE_Y (g MJ^{-1})	0.55a	0.56a	0.59a	0.67a	0.57a	0.56a
RUE_{DM} (g MJ^{-1})	1.29a	1.26a	1.38b	1.51a	1.31a	1.26a
RP_Y (g MJ^{-1})	0.21a	0.15b	0.25a	0.20b	0.20a	0.18b
RP_{DM} (g MJ^{-1})	0.48a	0.35b	0.57a	0.46b	0.45a	0.40b

Means followed by the same letter within an ISI level are not significantly different. Tukey ($\alpha = 0.05$).

[a] Intensification sequence index, i.e. the ratio between the number of crops in the sequence and its duration in years. Means followed by the same letter within an ISI level are not significantly different. Tukey ($\alpha = 0.05$).

[b] Maize proportion, i.e. the ratio of number of maize crops in the sequence and crop sequence duration.

Table 5
Water productivity and its components in crop sequences varying in intensification level simulated using a 30 years series of historical weather records of Balcarce, Argentina. ET, evapotranspiration; WUE_{DM}: water use efficiency for dry matter; WUE_Y: water use efficiency for grain yield; WP_{DM}: water productivity for dry matter; WP_Y: water productivity for grain yield; C_{WATER}: water capture efficiency. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

Variable	Sequence					
	W/S (2)[a] [0][b]	W–S (1) [0]	W/S–M (1.5) [0.5]	W–S–M (1) [0.33]	W/S–M–S (1.33) [0.33]	W–S–M–S (1) [0.25]
Annual ET (mm yr^{-1})	607a	423b	554a	453b	522a	456b
C_{WATER}	0.67a	0.46b	0.60a	0.50b	0.57a	0.50b
WUE_Y (g m^{-2} mm^{-1})	0.87a	0.92a	1.11a	1.13a	0.96a	0.97a
WUE_{DM} (g m^{-2} mm^{-1})	2.04a	2.07a	2.60a	2.55a	2.20a	2.20a
WP_Y (g m^{-2} mm^{-1})	0.58a	0.42b	0.67a	0.56b	0.55a	0.49b
WP_{DM} (g m^{-2} mm^{-1})	1.35a	0.96b	1.57a	1.27b	1.26a	1.10b

Means followed by the same letter within an ISI level are not significantly different. Tukey ($\alpha = 0.05$).

[a] Intensification sequence index, i.e. the ratio between the number of crops in the sequence and its duration in years. Means followed by the same letter within an ISI level are not significantly different. Tukey ($\alpha = 0.05$).

[b] Maize proportion, i.e. the ratio of number of maize crops in the sequence and crop sequence duration.

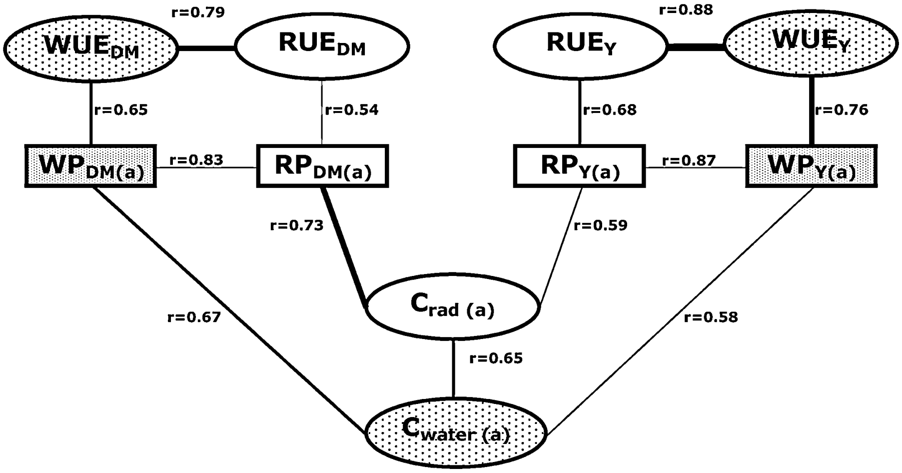

Fig. 2. Relationship among water (grey background) productivity (rectangles) and radiation (white background) for yield (*Y*) and dry matter (DM) on an annual basis and its components (ovals). *r*: correlation coefficient. Thinness of union lines within components represents the magnitude of association. All relationships were significant at $P < 0.0001$.

of annual rainfall in W/S as compared to 46% in W–S (Fig. 5a). Using the ET-rainfall benchmark of Zhang et al. (2001), sequences with ISI > 1 yr^{-1} were close to the benchmark for grassland systems (Fig. 5). Moreover, W/S sequence with ISI = 2 yr^{-1} tend to have similar annual ET in relation to annual rainfall than systems based on trees (Fig. 5a). All sequences with ISI > 1 yr^{-1} had less excess water than their counterparts with ISI = 1 yr^{-1} (Fig. 5a–c).

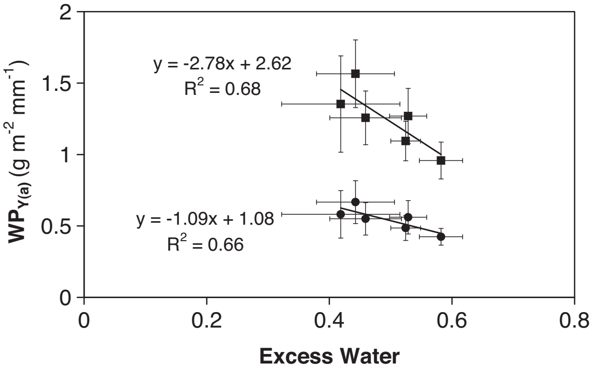

Fig. 3. Relationship between excess water and water productivity for yield (circles) and for dry matter (squares) on an annual basis. Excess water represents runoff + deep drainage expressed as proportion of annual rainfall.

3.3. Simulated annual yield of several crop sequences

Highest annual grain yields were reached by W–M and W/S–M, whereas these sequences did not differ from W/S or the traditional sequence W–S–W–M (Table 6). Lowest yields were obtained by W–S and W/S–S. Similarly, highest glucose yields were obtained by W–M and W/S–M, intermediate by W/S, W–S–M, W–S–W–M and W/S–M–S and lowest by W/S–S and W–S (Fig. 6 and Table 6).

Simulated crop yield of all crop sequences was higher than yield estimated in continuous crop yield-basis (Table 6). Moreover, the increase in sequences that include double crop (W/S) was up to two-fold than their counterparts (Table 6 and Fig. 7). Variation in maize glucose yield accounted for most of the variation in crop sequences that included it (Table 7). In sequences that did not include maize, wheat crop glucose yield accounted for most of the variation.

Cumulative frequency of relative yield was lower in sequences that included W/S (Fig. 8). Likewise, in half of simulated years at least 65% of attainable yield was reached in sequences including W/S, whereas in their counterparts with ISI = 1 yr^{-1}, 75–85% of attainable yield was reached. However, owing that maximum yield was higher in sequences that included W/S, in half of the simulated years these sequences had a glucose yield at least as high as 7000–8000 kg ha^{-1} yr^{-1} whereas their counterparts with ISI = 1 yr^{-1} only reached 6000–7000 kg ha^{-1} yr^{-1}. Differences in grain and glucose yield between sequences within each pair were higher as ISI increased (Fig. 8 and Table 6).

Table 6
Simulated grain and glucose yield; and expected grain and glucose yield in base of continuous crop yield in different crop sequences in Balcarce, Argentina. Expected grain and glucose yield were estimated as a weighted mean of continuous crop yields and the respective crop sequence duration. Bracketed values are indicating the increase (%) of simulated values respect of expected values. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

Sequence	Simulated yield (kg ha^{-1} yr^{-1})		CV of grain yield (%)	Expected yield in base of continuous crop (kg ha^{-1} yr^{-1})	
	Glucose	Grain		Glucose	Grain
W/S	7739 (41)b	5255 (46)bc	31	5485	3598
W–S	6039 (10)d	3878 (8)f	12	5485	3598
W/S–M	8269 (16)a	6158 (16)ab	25	7152	5327
W–S–M	7114 (8)b	5138 (8)cde	21	6596	4750
W/S–M–S	7065 (15)bc	5030 (17)cde	20	6144	4308
W–S–M–S	6394 (7)cd	4460 (8)ef	17	5979	4131
W–S–W–M	7440 (12)b	5383 (12)bcd	14	6657	4794
W/S–S	5903 (23)e	3775 (29)f	20	4807	2935
S–M	6668 (3)bc	4890 (5)def	32	6474	4663
W–M	8705 (11)a	6725 (12)a	19	7830	5990
Continuous crops					
W	6841	4925			
S	4129	2271			
M	8818	7055			

Means followed by the same letter within a column are not significantly different. Tukey ($\alpha = 0.05$).

In 75% of simulated years attainable yield of soybean and maize in continuous crops exceeded 40% of maximum (Fig. 8a), whereas in half of years were higher than 70% of maximum. It is worth noting that yield of soybean in continuous crop was simulated for optimum sowing dates, and therefore it is more adequate to compare it with soybean as a single crop per year instead of soybean as a second crop in a year. Attainable yield of wheat in continuous crop was less than 75% of maximum in only 25% of simulated years, whereas in half of years attainable yield was higher than 80%.

Sequences S–M and W/S–S had less than 55% of maximum attainable yield in 25% of simulated years, whereas in a half of years they were higher than 70% (Fig. 8c). Sequences W–M and W–S–W–M yielded 65–75% of maximum attainable yield 25% of years, whereas in half of years attainable yield was higher than 80% (Fig. 8c), i.e. as higher as wheat continuous crop (Fig. 8a).

In 75% of the years glucose yield in continuous crops were higher than 3000 kg ha^{-1} for soybean and 6000 kg ha^{-1} for wheat and maize (Fig. 8b). However, maize glucose yield were higher than 9000 kg ha^{-1} in half of the years whereas wheat and soybean did not reach that value.

Traditional sequences of our region (W–M and W–S–W–M), in turn, yielded more than 7000 and 8000 kg ha^{-1} in 75% of years (Fig. 8d), whereas W/S–S and S–M only reached 5000 kg ha^{-1}. In a half of years W/S–S, S–M, W–S–W–M and W–M sequences yielded more than 6000, 7000, 7500 and 8500 kg ha^{-1}, respectively.

4. Discussion

4.1. Performance of simulation models

Yield and dates of key phenostages of wheat, soybean and maize were simulated acceptably (Table 2). RMSE for soybean and wheat were comparable to reported values (Mavromatis et al., 2001; Timsina et al., 1998; Monzon et al., 2003). The increase of RMSE for late developmental stages could be related to the increased inaccuracy in defining such stages, particularly physiological maturity, a carry over of errors through the season or both. Simulation of some variables was biased, mainly time of silking (R1) in maize accounting for 53% of MSE.

The close match between actual and modelled ET (Fig. 1b and d) suggests that the model captured the dynamics of soil water, including the transfer of soil moisture conditions from wheat to soybean crop. Also, the cumulative IPAR simulated was close to observed cumulative IPAR in the sequential wheat/soybean double crop (Fig. 1a and c). These tests indicated the models perform with sufficient accuracy for the objectives of this study, with errors which are within the limits of experimental errors for most variables. Reasonable estimates of yield, dry matter, capture of water and radiation allow for some confidence in the derived variables to quantify resource productivity (Eqs. (2) and (3)). The consistency between our modelled relation between rainfall and ET, and the empirical relationship reported by Zhang et al. (2001) (Fig. 5) reinforces this conclusion. Simulated resource productivity (WP and RP) and its components (C_{WATER}, C_{RAD}, WUE and RUE) shown in Tables 4 and 5 were comparable with experimental values (Caviglia et al., 2004). Likewise, simulated RUE and WUE for both yield and dry matter were consistent with experimental measurements (Daniels and Scott, 1991; Andrade, 1995; Sinclair and Muchow, 1999; Caviglia and Sadras, 2001). Collectively, our tests indicate that our simulations captured a good part of abiotic effects of rotations in yield, chiefly those related to sowing date and the water and nitrogen economies of crops, but did not account for extreme events and the biological effects of rotations (Hall and Sadras, 2009).

4.2. Cropping sequences intensification and resources productivity

Cropping intensification involving wheat/soybean double crop improved water and radiation annual productivities as a consequence of an improved ability to capture resources (C_{WATER} and C_{RAD}) (Tables 4 and 5 and Fig. 2). Despite the close association (Fig. 2) between $\mathrm{WP_Y}$ and $\mathrm{RP_Y}$ and resource use–efficiencies ($\mathrm{WUE_Y}$ and $\mathrm{RUE_Y}$), these relationships were mainly driven by variation in crop composition, particularly maize proportion, rather than variation in degree of intensification.

Sequences which had the higher WP and RP did not necessarily had the higher $\mathrm{WUE_Y}$ and $\mathrm{RUE_Y}$ (Tables 4 and 5). This reflects that the concepts of water and radiation productivity, based on the annual availability of resources, were more suitable to characterize the performance of cropping sequences than the classical resource use efficiencies based on the amount of captured resource. In fact, the classical approach ignores the resources available out of the growing season.

Annual ET and annual capture of PAR both increased with increasing ISI, but considerable amounts of resources remained unused, i.e. 33–43% of annual rainfall and 58–65% of annual

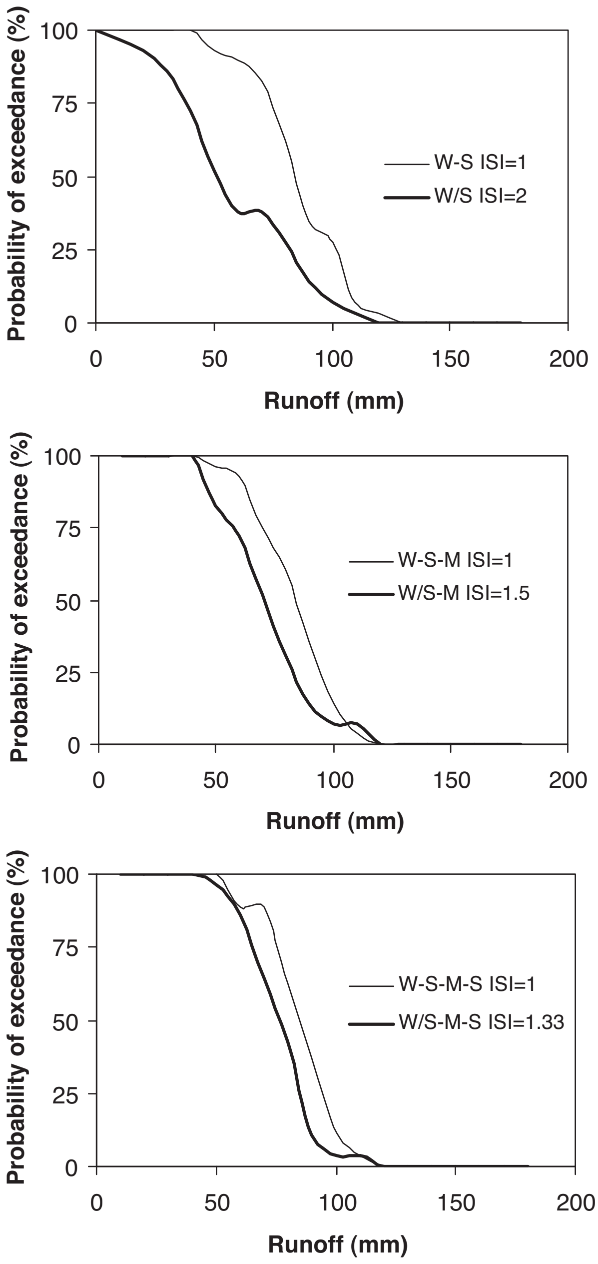

Fig. 4. Average in-season runoff in three pairs of crop sequences differing in the intensification index (ISI) at Balcarce, Argentina. W/S: wheat/soybean sequential double crop, W: wheat, S: soybean, M: maize. Thin line represents sequences with ISI = 1 yr^{-1}, strong line represent sequences with ISI > 1 yr^{-1}.

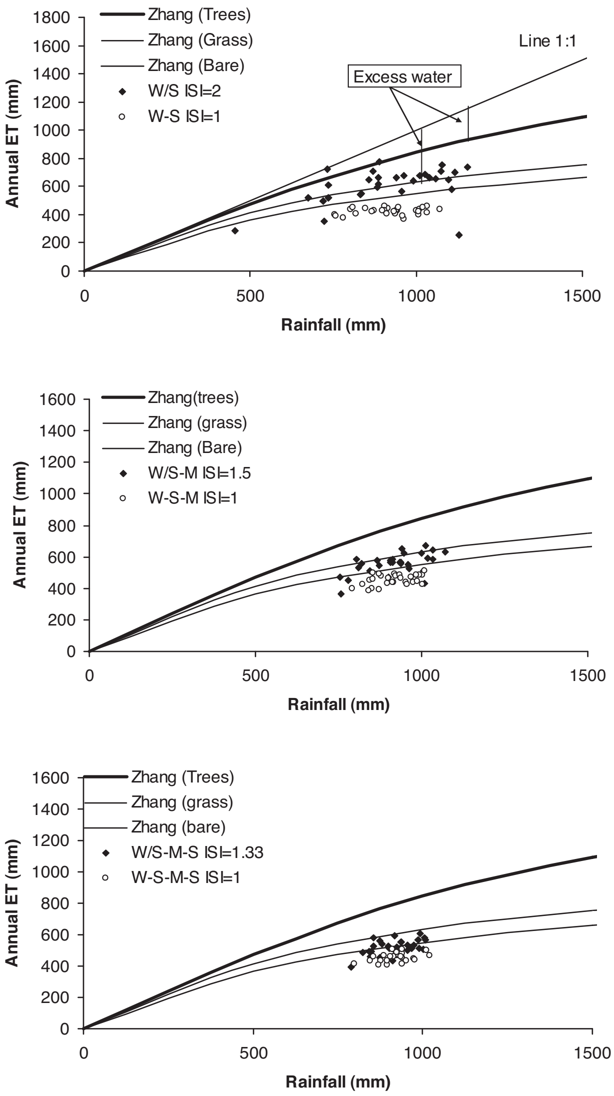

Fig. 5. Annual evapotranspiration (ET) as a function of annual rainfall in three pairs of crop sequences differing in the intensification index (ISI) at Balcarce, Argentina. W/S: wheat/soybean sequential double crop, W: wheat, S: soybean, M: maize. Thin line represents the function for bare soil, strong line represents the function for trees and dotted line represents the function for grasses. Functions were fitted according to Zhang et al. (2001).

incident PAR, even in sequences with two crops per year (ISI = 2 yr^{-1}) (Tables 4 and 5).

For the cropping systems under study, most of the annual rainfall was accounted for crop evapotranspiration. For annual rainfall between 300 and 500 mm yr^{-1}, Gregory et al. (1992) showed that increasing rainfall leads to reductions in the proportion of ET as a component of the water balance. Studying water balances of catchments from diverse climate, soil, and vegetation conditions, Zhang et al. (2001) found a strong curvilinear relationship between ET and rainfall, i.e. in sites with annual rainfall from 500 to 2000 mm, ET increased from 400 to 800 mm, whereas “excess water” (runoff + drainage) increased from 100 to 1200 mm. There is, in consequence, a trend to increase other components of water balance than ET with increasing annual rainfall. Therefore, in sub-humid to humid environments, like ours, it is advisable to

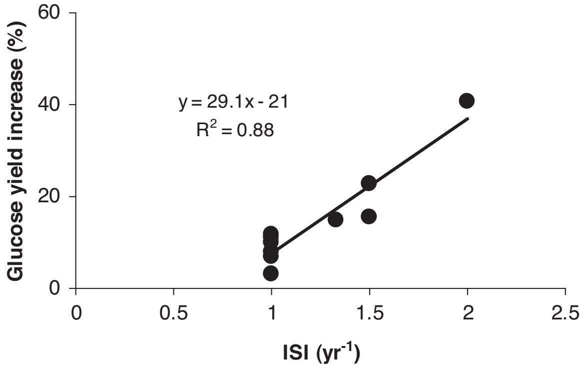

Fig. 6. Proportional yield increase in annual glucose yield sequence respect to estimate using continuous crop yield as affected by intensification sequence index (ISI).

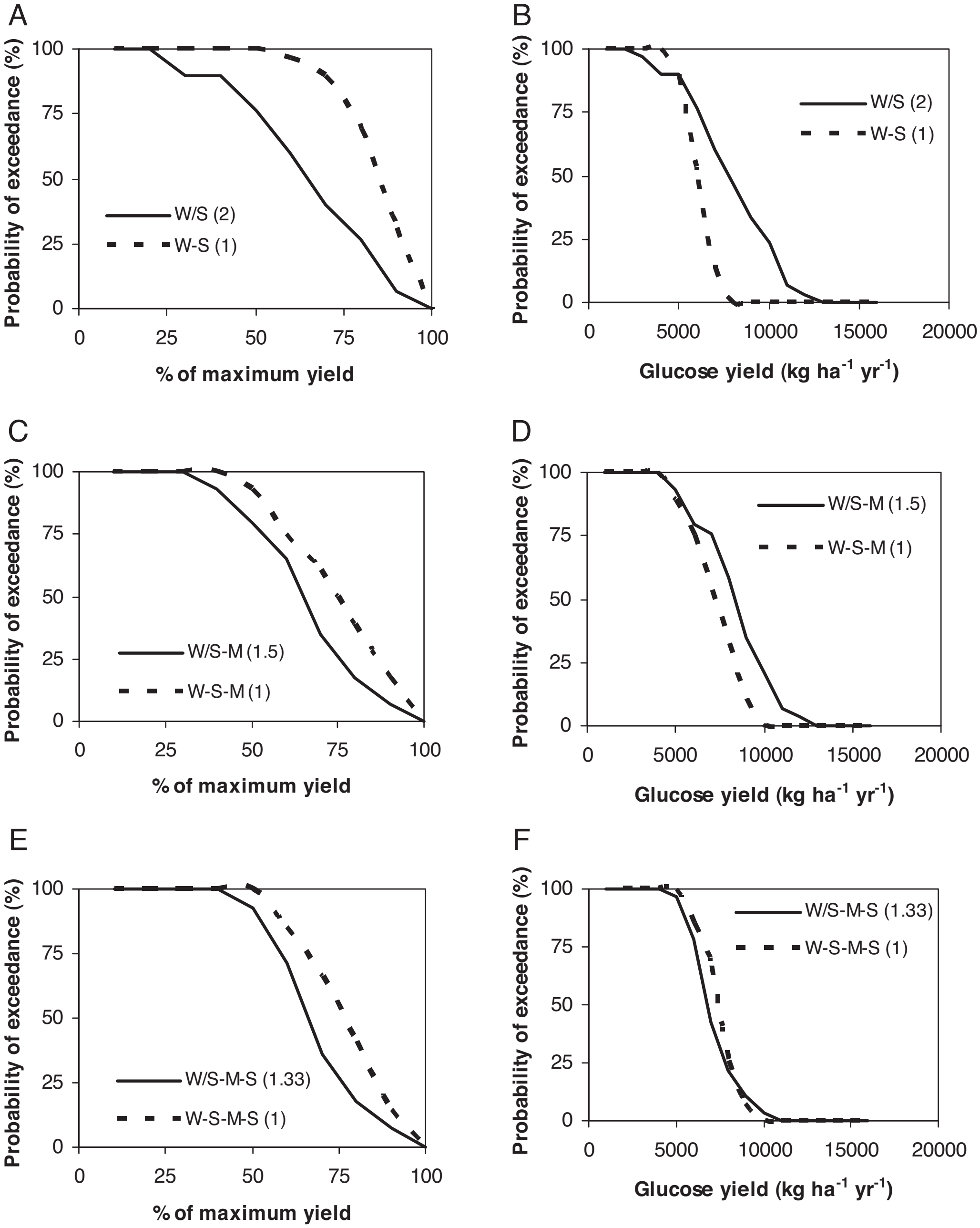

Fig. 7. Cumulative probability, using a long term simulation (30 years), to exceed a percentage of maximum attainable yield (left) or an annual glucose yield (right) in three crop sequences at Balcarce, Argentina. Crop sequences had the following composition: wheat and soybean (a) and (b); wheat, soybean and maize (c) and (d) and; wheat, soybean, maize and soybean (e) and (f). Dotted line indicate sequences with ISI = 1 yr^{-1}, filled line otherwise. Bracketed values indicate ISI of respective sequence. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

Table 7
Percentage of variation accounted for annual glucose yield of each crop as component of a crop sequence (partial R^2). Bracketed values are indicating probability (P) of parameters. W: wheat, S: soybean, M: maize, W/S: wheat/soybean double crop.

	Wheat	Soybean	Maize	Wheat	Soybean
W/S	60 (<0.0001)	40 (<0.0001)			
W–S	64 (<0.0001)	36 (<0.0001)			
W/S–M	20 (0.0001)	12 (<0.0001)	68 (<0.0001)		
W–S–M	10 (<0.007)	13 (<0.09)	77 (<0.0001)		
W/S–M–S	20 (0.0002)	13 (<0.0001)	52 (<0.0001)		15 (<0.0001)
W–S–M–S	25 (<0.0001)	10 (<0.0002)	55 (<0.0001)		10 (<0.0005)
W–S–W–M	12 (<0.0001)	10 (<0.0001)	61 (<0.0001)	17(< 0.0002)	
W/S–S	28 (<0.0033)	32 (<0.0001)			40 (<0.0001)
S–M		21 (<0.0001)	79 (<0.0001)		
W–M	23 (<0.0001)		77 (<0.0001)		

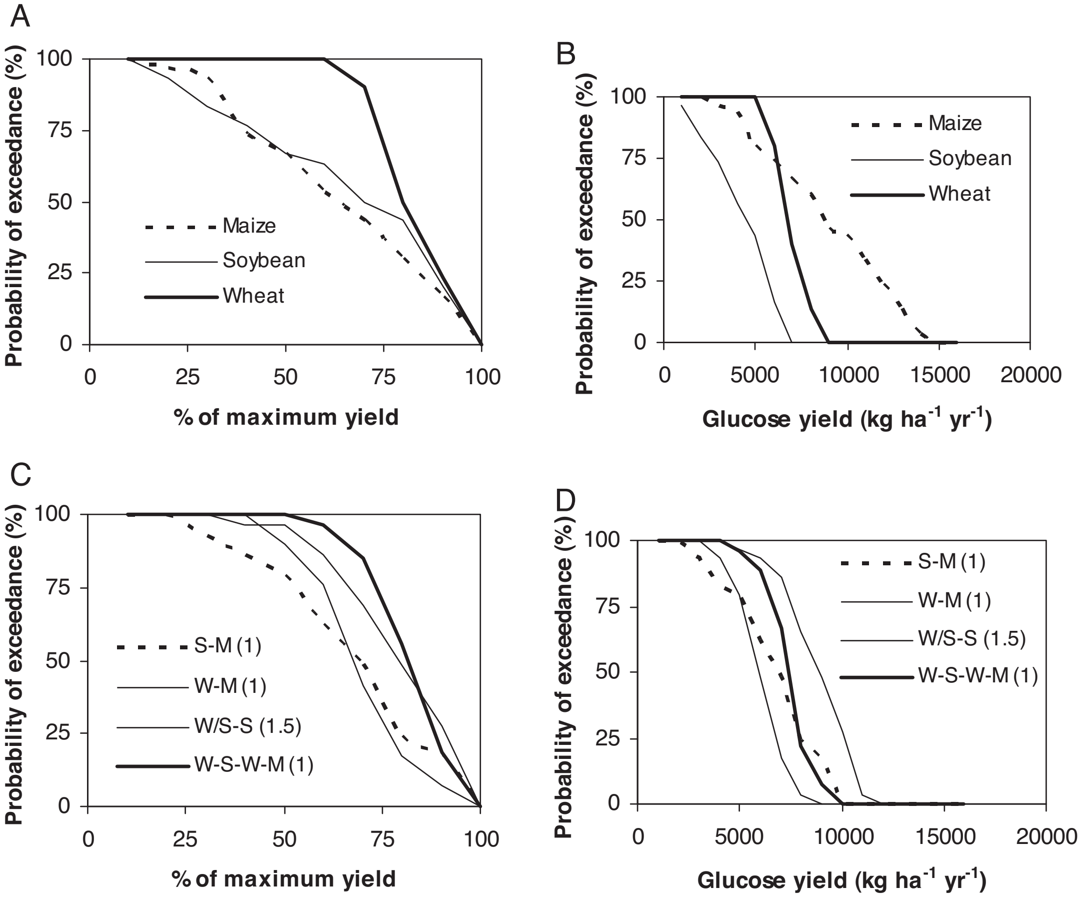

Fig. 8. Cumulative probability, using a long term simulation (30 years), to exceed a percentage of maximum attainable yield (left) or an annual glucose yield (right) of crop sequences at Balcarce, Argentina. a and b: wheat, soybean and maize continuous crops. c and d: W–M; W/S–S; S–M and W–S–W–M. Bracketed values indicate ISI of respective sequence. W: wheat, S: soybean, and M: maize, W/S: wheat/soybean double crop.

adopt cropping systems able to capture more water to increase water productivity. Our results demonstrated that sequences with ISI > 1.33 yr^{-1} were as able as grassed systems to use the annual rainfall as ET (Fig. 5), revealing that intensification is a powerful tool for improving water use when annual rainfall usually exceeds the ET of a sole annual crop.

The strong relationship between C_{WATER} and C_{RAD}, and the contrast between storable (water) and non-storable (radiation) resources (Caviglia et al., 2004) reinforce the concept that increased resource productivity requires improved radiation capture. The importance of the inclusion of more efficient crops to transform captured resource such as maize should be emphasized.

Previous reports have documented a relationship between water- and radiation-use efficiency at the level of single crops (Sadras et al., 1991; Caviglia and Sadras, 2001) and for wheat/soybean double crops (Caviglia et al., 2004). In this paper we confirmed that the relationship remains when scaling-up to an entire crop sequence. Moreover, components of resource (water and radiation) productivity, capture and use efficiencies, were closely linked (Fig. 3). The key underlying these relationships is that solar radiation, the main component of atmospheric demand, drives both water use (ET) and crop growth.

The improved WUE and RUE in sequences that contain maize are mainly related with the C4 photosynthetic metabolism and grain composition. Differences among cereals and oil crops in resource use efficiencies as a result of their photosynthetic metabolism and energetic cost to produce oil and protein in grain are well established (Andrade, 1995; Sinclair and Muchow, 1999; Caviglia et al., 2004; Stockle and Kemanian, 2009).

4.3. Yield per unit area and time in several crop sequences

Traditional crop sequences of our region (i.e. W–M, W–S and W–M–W–S; Fig. 8c and d) had similar glucose yield and stabilities (CV) than sequences with high cropping intensity and maize proportion (Fig. 7). Likewise, it was evident the role of wheat to contribute to stability and of maize to contribute to productivity. Against the backdrop of the role of risk minimization in the evolution of cropping systems (Sadras and Roget, 2004), we can understand the former massive adoption of cropping sequences that alternate stable and high yielding wheat with a summer crop (sunflower, maize or soybean) in the next year (ISI = 1 yr^{-1}). The role of wheat conferring stability in rainfed cropping systems has been established for Mediterranean environments (Ryan et al., 2009), but there is scarce quantitative evidence for systems with summer or annually uniform rainfall patterns. In our region, the high yield potential of wheat has been linked to favourable photothermal quotient (Fischer, 1985; Magrin et al., 1993), but there are no studies on wheat yield stability, which might be high because of its winter-spring growing season with low-moderate water demand (Sadras and Calviño, 2001).

Owing to its high yield and low yield stability, maize proportion accounted for the most of variation of the annual yield in sequences (Fig. 8a and b). Calviño et al. (2003b) established quantitative relationships between water availability during a critical period bracketing silking and maize yield in our region. Likewise, consistently with our results maize yield was more sensitive to soil depth than wheat (Sadras and Calviño, 2001). Wheat yield was only relevant as source of variation in the performance of sequences that did not include maize (Table 7).

Even though soybean yields had a low stability comparable to that of maize, this did not contribute much to annual yield variation because of its low contribution to annual yield of sequences (Table 7). However, the contribution of soybean to annual yield variation increased in sequences lacking the maize component.

4.4. Role of intensification on components of water budget

Studies in arid and semiarid zones strongly suggested that intensification of cropping systems can contribute to reduce deep drainage (e.g. Gregory et al., 2002; Sadras and Roget, 2004). Gregory et al. (1992) and Zhang et al. (2001), however, have clearly showed that components of water balance change their contribution according to the amount of annual precipitation. Thus, in zones with high annual rainfall a higher proportion of runoff and deep drainage could be anticipated. However, in two seasons of experimental work at Balcarce where we compared wheat, soybean and W/S double crop during two growing seasons, water budgets indicated no deep drainage despite large rainfall events (Caviglia et al., 2004). Similarly, no events of deep drainage were recorded in our simulation experiments even during fallow periods. Deep drainage through preferential fluxes, however, cannot be excluded.

Simulated superficial runoff was associated with rainfall amount, in coincidence with others regional results (e.g. Irigoyen, 1998). Annual water loss, estimated as $1 - C_{\mathrm{WATER}}$, was reduced by cropping intensification improving directly $\mathrm{WP_Y}$ (Fig. 3). Our result evidenced a substantial reduction of in-season runoff in sequences with higher ISI (Fig. 4). Although part of water loss during fallow periods can be attributed to soil evaporation, a reduced amount of superficial runoff could reduce soil erosion and nutrient runoff to water flows. Thus, intensification of cropping sequences is critical not only for the improvement of productivity and system efficiency but also to reduce environmental outcomes (Gregory et al., 1992; Nosetto et al., 2012).

4.5. Potential benefits of intensification

Although no attempts to simulate the effect of crop sequences on soil organic matter were made, we confirmed that annual input of crop residues to soil increased with both intensification and maize proportion (Table 3). Similarly, Franzluebbers et al. (1998) reported a linear relationship between cropping intensity and annual carbon inputs to the soil in humid area of Texas (US). Wood et al. (1991) documented a higher nitrogen and carbon potential mineralization in sequences with high ISI ($1.33\ \mathrm{yr}^{-1}$) than in typical US-great plains wheat-fallow ($\mathrm{ISI} = 0.5\ \mathrm{yr}^{-1}$) sequences under no-tillage systems. In our region, a higher production of crop residues has been documented in double than in sole crops (Caviglia et al., 2011).

There is a wide agreement about advantages of crop rotation on sustainable agricultural production. Although the underling mechanism involved in the complex "rotation effect" remains unclear, enhanced soil organic matter and improved soil physical parameters are likely factors (Bullock, 1992; Karlen et al., 1994). Other environmental benefits of crop rotation include improvement of biological diversity, nutrient cycling, microclimate regulation, opportunities for control of weeds, diseases, and insects, and detoxification of chemical compounds (Karlen et al., 1994; Altieri, 1999). Intensification of crop sequences can also contribute to increase spatial biodiversity owing to the coexistence of higher number of crop in a determinate area in a given time (Karlen et al., 1994) in opposition to a crop sequences based in a few crops.

Three types of intensification have been pointed out (Gregory et al., 2002). Type I is typical of regions with high rural population and low technology inputs. Type II address maximizing food production and has been associated with the "green revolution" characterized by intense use of input and a low environment concern. Type III has been defined as "doubly green revolution" oriented to maximize profits using technologies more friendly with the environment. The focus of Gregory et al. (2002) classification, however, is based on a single crop per season. Here we showed that intensification involving multiple cropping can raise yield per unit area and time as much as 13–35%. The intensive systems evaluated in this work are compatible with Gregory's type III, i.e. oriented only to increase the design of crop sequence without an input increase in systems typically well managed where only small gains are expected by input additions. A more intense use of highly productive lands could help to alleviate pressure on more fragile, less productive, agroecosystems (Caviglia and Andrade, 2010). In contrast to multiple cropping in subsistence systems of Central America, Africa and Asia, the inclusion of wheat/soybean double crop into high yielding sequences of the South-eastern Pampas was an appropriate way to reach an annual yield as high as that in traditional sequences based on a single crop per year. Also in contrast to subsistence agriculture, multiple cropping in this high-tech system relies on fully mechanized practices (Calviño and Monzon, 2009).

There is a growing global concern about the environmental contamination by chemical compounds used in agriculture, which may be more needed as cropping intensity increases. However, the socio-economic conditions are quite different in developed countries with strongly subsidized agricultures than in the non-subsidised agriculture of Argentina. Here, productive, environmental, and socio-economic sustainability only can be reached thorough a rational use of input and maximizing yield per unit land and time, according to the concepts of type III of intensification (Gregory et al., 2002).

Acknowledgements

This work was funded by INTA and FONCyT. OPC and FHA are members of CONICET, the Research Council of Argentina

References

Aase, J.K., Pikul Jr., J.L., 2000. Water use in a modified summer fallow system on semiarid Northern Great Plains. Agric. Water Manage. 43, 345–357.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19–31.

Andrade, F.H., 1995. Analysis of growth and yield of maize, sunflower and soybean grown at Balcarce, Argentina. Field Crops Res. 41, 1–12.

Barbieri, P.A., Sainz Rozas, H., Andrade, F.H., Echeverria, H.E., 2000. Row spacing effects at different levels of nitrogen availability in maize. Agron. J. 92, 283–288.

Bullock, D.G., 1992. Crop rotation. Crit. Rev. Plant Sci. 11, 309–326.

Calviño, P.A., Monzon, J.P., 2009. Farming systems of Argentina: yield constraints and risk management. In: Sadras, V.O., Calderini, D.F. (Eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. Academic Press, San Diego, pp. 55–70.

Calviño, P.A., Sadras, V.O., Andrade, F.H., 2003a. Development, growth and yield of late-sown soybean in the southern Pampas. Eur. J. Agron. 19, 265–275.

Calviño, P.A., Andrade, F.H., Sadras, V.O., 2003b. Maize yields as affected by water availability, soil depth and crop management. Agron. J. 95, 275–281.

Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28, 315–358.

Caviglia, O.P., Andrade, F.H., 2010. Sustainable intensification of agriculture in the Argentinean Pampas: capture and use efficiency of environmental resources. Am. J. Plant Sci. Biotechnol. 3, 1–8.

Caviglia, O.P., Sadras, V.O., 2001. Effect of nitrogen supply on crop conductance, water- and radiation- use efficiency of wheat. Field Crops Res. 69, 259–266.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2004. Intensification of agriculture in the south-eastern Pampas. I. Capture and efficiency in the use of water and radiation in double-cropped wheat–soybean. Field Crops Res. 87, 117–129.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2011. Grain yield and quality of wheat and soybean in sole- and double-cropping. Agron. J. 103, 1081–1089.

Cirilo, A., Andrade, F.H., 1994. Sowing date and maize productivity: I. Crop growth and dry matter partitioning. Crop Sci. 34, 1039–1043.

Daniels, M.B., Scott, H.D., 1991. Water use efficiency of double-cropped wheat and soybean. Agron. J. 83, 564–570.

Díaz-Ambrona, C.G.H., O'Leary, G.J., Sadras, V.O., O'Connell, M.G., Connor, D.J., 2005. Environmental risk analysis of farming systems in a semi-arid environment: effect of rotations and management practices on deep drainage. Field Crops Res. 94, 257–271.

Evans, L.T., 1993. Crop Evolution, Adaptation and Yield. Cambridge University Press, Cambridge, pp. 500.

Evans, L.T., 2003. Agricultural intensification and sustainability. Outlook Agric. 32, 83–89.

FAO, 2011. FAOSTAT. Agricultural Data. FAO, Rome, Available online at http://www.faostat.fao.org/ (verified 19.04.11).

Farahani, H.J., Peterson, G.A., Westfall, D.G., 1998. Dryland cropping intensification: a fundamental solution to efficient use of precipitation. Adv. Agron. 64, 197–223.

Fehr, W.R., Caviness, C.E., 1977. Stages of soybean development. In: Spec. Rep. 80. Iowa Agric. Home Econ. Exp. Stn. Iowa State Univ., Ames.

Fila, G., Bellocchi, G., Acutis, M., Donatelli, M., 2003. Irene: a software to evaluate model performance. Eur. J. Agron. 18, 369–372.

Fischer, R.A., 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci. 105, 447–461.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1998. In situ and potential CO_2 evolution from a Fluventic Ustochrept in southcentral Texas as affected by tillage and cropping intensity. Soil Till. Res. 47, 303–308.

Gregory, P.J., Tennant, D., Hamblin, A.P., Eastham, J., 1992. Components of the water balance on duplex soils in Western Australia. Aust. J. Exp. Agr. 32, 845–855.

Gregory, P.J., Ingram, J.S.I., Andersson, R., Betts, R.A., Brovkin, V., Chase, T.N., Grace, P.R., Gray, A.J., Hamilton, N., Hardy, T.B., Howden, S., Jenkins, M.A., Meybeck, M., Olsson, M., Ortiz-Monasterio, I., Palm, C.A., Payn, T.W., Rummukainen, M., Schulze, R.E., Thiem, M., Valentin, C., Wilkinson, M.J., 2002. Environmental consequences of alternative practices for intensifying crop production. Agr. Ecosyst. Environ. 88, 279–290.

Hall, A.J., Sadras, V.O., 2009. Whither crop physiology? In: Sadras, V.O., Calderini, D.F. (Eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. Academic Press, San Diego, pp. 545–570.

Halvorson, A.D., Black, A.L., Krupinsky, J.M., Merrill, S.D., 1999. Dryland winter wheat response to tillage and nitrogen within an annual cropping system. Agron. J. 91, 702–707.

Hergert, G.W., Klocke, N.L., Petersen, J.L., Nordquist, P.T., Clark, R.T., Wicks, G.A., 1993. Cropping systems for stretching limited irrigation supplies. J. Prod. Agric. 6, 520–529.

Hoogenboon, G., Jones, J.W., Wilkens, P.W., Batchelor, W., Bowen, W.T., Hunt, L.A., Pickering, N., Singh, U., Godwin, D.C., Baer, B., Boote, K.J., Ritchie, J.T., White, J.W., 1994. Crop models. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), DSSAT v. 3, vol. 2-2. University of Hawai, Honolulu, HI, USA.

Hoogenboon, G., Wilkens, P.W., Thornton, P.K., Jones, J.W., Hunt, L.A., Inamura, D.T., 1999. Decision support system for agrotechnology transfer v.3.5. In: Hoogenboon, G., Wilkens, P.W., Tsuji, G.Y. (Eds.), DSSAT, Version 3, vol. 4. University of Hawai, Honolulu, HI, pp. 1–36.

Huang, M., Shao, M., Zhang, L., Li, Y., 2003. Water use efficiency and sustainability of different long-term crop rotation systems in the Loess Plateau of China. Soil Till. Res. 72, 95–104.

Hunt, L.A., Pararajasingham, S., Jones, J.W., Hoogenboon, G., Inamura, D.T., Ogoshi, R.M., 1993. Gencalc: software to facilitate the use of crop models for analyzing field experiments. Agron. J. 85, 1090–1094.

Irigoyen, A.I., 1998. La precipitación efectiva como componente del balance de agua en un paleudol petrocalcico de Balcarce. FCA-UNMP, pp. 117 (Tesis M.Sc.).

Jones, J.W., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station, TX, pp. 194.

Jones, O.R., Popham, T.W., 1997. Cropping and tillage systems for dryland grain production in the Southern High Plains. Agron. J. 89, 222–232.

Karlen, D.L., Varvel, G.E., Bullok, D.G., Cruse, R.M., 1994. Crop rotations for the 21st Century. Adv. Agron. 53, 1–45.

Kobayashi, K., Us Salam, M., 2000. Comparing simulated and measured values using mean squared deviation and its components. Agron. J. 92, 345–352.

Magrin, G.O., Hall, A.J., Baldy, C., Grondona, M.O., 1993. Spatial and interannual variations in the photothermal quotient: implications for the potential kernel number of wheat crops in Argentina. Agric. Forest Meteorol. 67, 29–41.

Mavromatis, T., Boote, K.J., Jones, J.W., Irmak, A., Shinde, D., Hoogenboom, G., 2001. Developing genetic coefficients for crop simulation models with data from crop performance trials. Crop Sci. 41, 40–51.

McFarlane, D., George, R.J., Farrington, P., 1992. Changes in the hydrological cycle. In: Hobbs, R.J., Saunders, D.A. (Eds.), Reintegrating Fragmented Landscapes: Towards Sustainable Production and Nature Conservation. Springer-Verlag, New York, pp. 146–186.

Montoya, J.C., Costa, J.L., Liedl, R., Bedmar, F., Daniel, P., 2006. Effects of soil type and tillage practice on atrazine transport through intact soil cores. Geoderma 137, 161–173.

Monzon, J.P., Sadras, V.O., Abbate, P.A., Caviglia, O.P., 2003. Modelling management strategies for wheat–soybean double crops in the south-eastern Pampas. Field Crops Res. 101, 44–52, http://dx.doi.org/10.1016/j.fcr.2006.09.007.

Nielsen, D.C., 1998. Comparison of three alternative oilseed crops for the Central Great Plains. J. Prod. Agric. 11, 336–341.

Nielsen, D.C., Vigil, M.F., Anderson, R.L., Bowman, R.A., Benjamin, J.G., Halvorson, A.D., 2002. Cropping system influence on planting water content and yield of winter wheat. Agron. J. 94, 962–967.

Nielsen, D.C., Vigil, M.F., Benjamin, J.G., 2011. Evaluating decision rules for dryland rotation crop selection. Field Crops Res. 120, 254–261.

Norwood, C., 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agron. J. 86, 558–563.

Nosetto, M.D., Jobbágy, E.G., Brizuela, A.B., Jackson, R.B., 2012. The hydrologic consequences of land cover change in central Argentina. Agric. Ecosyst. Environ. 154, 2–11, http://dx.doi.org/10.1016/j.agee.2011.01.008.

Nosetto, M.D., Jobbágy, E.G., Paruelo, J.M., 2005. Land use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. Global Change Biol. 11, 1101–1117.

Nosetto, M.D., Jobbágy, E., Tóth, T., Jackson, R., 2008. Regional patterns and controls of ecosystem salinization with grassland afforestation along a rainfall gradient. Global Biogeochem. Cycles 22, GB2015.

Nosetto, M.D., Jobbágy, E.G., Jackson, R., Sznaider, G., 2009. Reciprocal influence of crops and shallow ground water in sandy landscapes of the Inland Pampas. Field Crops Res. 113, 138–148.

Novelli, L.E., Caviglia, O.P., Melchiori, R.J.M., 2011. Impact of soybean cropping frequency on soil carbon storage in Mollisols and Vertisols. Geoderma 167, 254–260.

Penning de Vries, F.W.T., 1972. Respiration and growth. In: Rees, A.P. (Ed.), Crop Processes in Controlled Environments. Academic Press, New York, pp. 327–347.

Piñeiro, G., Perelman, S., Guerschman, J.P., Paruelo, J.M., 2008. How to evaluate models: observed vs. predicted or predicted vs. observed? Ecol. Model. 216, 316–322.

Portela, S.I., Andriulo, A.E., Jobbágy, E.G., Sasal, M.C., 2009. Water and nitrate exchange between cultivated ecosystems and groundwater in the Rolling Pampas. Agric. Ecosyst. Environ. 134, 277–286.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Till. Res. 43, 131–167.

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

Ritchie, J.T., Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: Willis, B. (Ed.), ARS Wheat Yield Project, ARS-38. US Department of Agriculture, ARS, Washington, DC, pp. 159–175.

Ryan, J., Ibrikci, H., Sommer, R., McNeill, A., 2009. Nitrogen in rainfed and irrigated cropping systems in the Mediterranean region. Adv. Agron. 104, 53–136.

Sadras, V.O., Calviño, P.A., 2001. Quantification of grain yield response to soil depth in soybean, maize, sunflower, and wheat. Agron. J. 93, 577–583.

Sadras, V.O., Roget, D., 2004. Production and environmental aspects of cropping intensification in a semiarid environment of southeastern Australia. Agron. J. 96, 236–246.

Sadras, V.O., Whitfield, D.M., Connor, D.J., 1991. Transpiration efficiency in crops of semi-dwarf and standard-height sunflower. Irrigation Sci. 12, 87–91.

Sadras, V.O., Baldock, J., Cox, J., Bellotti, B., 2004. Crop rotation effect on wheat grain yield as mediated by changes in the degree of water and nitrogen co-limitation. Aust. J. Agric. Res. 55, 599–607.

Sadras, V.O., Calderini, D.F., Connor, D.J., 2009. Sustainable agriculture and crop physiology. In: Sadras, V.O., Calderini, D.F. (Eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. Academic Press, San Diego, pp. 1–20.

Sainz Rosas, H., Echeverría, H.E., Studdert, G.A., Dominguez, G., 2000. Evaluation of presidedress soil nitrogen test for no-tillage maize fertilized at planting. Agron. J. 92, 1176–1183.

SAS Institute, 2003. SAS Procedures For Personal Computers. v.9.1. SAS Inst., Cary, NC.

Shaver, T.M., Peterson, G.A., Sherrod, L.A., 2003. Cropping intensification in dryland systems improves soil physical properties: regression relations. Geoderma 166, 149–164.

Sinclair, T.R., Muchow, R.C., 1999. Radiation use efficiency. Adv. Agron. 65, 215–265.

Smith, R., Gross, K., Robertson, G., 2008. Effects of crop diversity on agroecosystem function: crop yield response. Ecosystems 11, 355–366.

Stockle, C.O., Kemanian, A.R., 2009. Crop radiation capture and use efficiency: a framework for crop growth analysis. In: Sadras, V.O., Calderini, D.F. (Eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. Academic Press, San Diego, pp. 145–170.

Studdert, G.A., Echeverria, H., 2000. Crop rotations and nitrogen fertilization to manage soil organic carbon dynamics. Soil Sci. Soc. Am. J. 64, 1496–1503.

Thornton, P.K., Hoogenboom, G., Wilkens, P.W., Bowen, W.T., 1995. A computer program to analyze multiple-season crop model outputs. Agron. J. 87, 131–136.

Timsina, J., Singh, U., Badaruddin, M., Meisner, C., 1998. Cultivar, nitrogen, and moisture effects on a rice–wheat sequence: experimentation and simulation. Agron. J. 90, 119–130.

Tisdall, J.M., Oades, J., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Wood, C.W., Peterson, G.A., Westfall, D.G., Cole, C.V., Willis, W.O., 1991. Nitrogen balance and biomass production of newly established no-till dryland agroecosystems. Agron. J. 83, 519–526.

Wright, A.L., Hons, F.M., 2004. Soil aggregation and carbon and nitrogen storage under soybean cropping sequences. Soil Sci. Soc. Am. J. 68, 507–513.

Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14, 415–421.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. The response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708.