Modelling yield response of a traditional and a modern barley cultivar to different water and nitrogen levels in two contrasting soil types

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Abstract. The importance of yield improvement at farm conditions is highly dependent on the interaction between genotype and environment. The aim of the present work was to assess the attainable yield of a traditional and a modern malting barley cultivar growing under a wide range of soil nitrogen (N) availabilities and different water scenarios (low, intermediate and high rainfall conditions during the fallow period and throughout the crop cycle) considering a 25-year climate dataset for two sites (a shallow and a deep soil) in the Pampas, Argentina. For that purpose, a barley model was first calibrated and validated and then used to expand field research information to a range of conditions that are not only much wider but also more realistic than experiments on experimental farms. Yield of the modern cultivar was at least equal to (under the lowest yielding conditions) or significantly higher (under most growing conditions) than that of the traditional cultivar. Averaged across all the scenarios, yield was ~20% higher in the modern than in the traditional cultivar. The average attainable yield represented 42% of the yield potential in the shallow and 79% in the deep soil profiles. Yield advantage of the high yielding cultivar was based on using N more efficiently, which not only determined higher attainable yields but also reduced the requirements of soil N to achieve a particular yield level. Farmers would face little risk in adopting higher yielding cultivars in both high and low yielding environments and even in the latter ones N fertilisation could be beneficial in most years.

Additional keywords: attainable yield, breeding by management interaction, grain nitrogen-use efficiency, malting barley, yield potential.

Introduction

Barley yield increased worldwide during the last 50 years from 1.9 to 2.5 Mg ha^{-1}, at a rate of 0.024 Mg ha^{-1} year^{-1} (estimated from the dataset of FAO 2010). The contribution of plant breeding to actual yield in temperate cereals has been estimated between 30 and 50% (Slafer *et al*. 1994; Bell *et al*. 1995; Abeledo *et al*. 2003*a*), while the other proportion has been ascribed to the improvement in agronomic practices (Slafer *et al*. 1994) and the interaction between cultivar and management (Evans and Fischer 1999). It is a matter of dispute in the literature whether modern cultivars do or do not represent an advantage over their older counterparts (or even landraces) at all growing conditions. For instance, there are several studies indicating that barley yields are reduced with replacement of landraces by high yielding cultivars in low yielding environments (Ceccarelli *et al*. 2001; Brancourt-Hulmel *et al*. 2005; Pswarayi *et al*. 2008). However, several studies reported that modern cultivars of barley out-yielded traditional cultivars across a wide range of environments (Abeledo *et al*. 2003*b*; Tambussi *et al*. 2005), a fact also well

documented for wheat (Ortiz-Monasterio *et al*. 1997; Calderini and Slafer 1999; Guarda *et al*. 2004; De Vita *et al*. 2007). Unravelling this controversy is especially relevant for barley farmers of many regions, who are reluctant to adopt modern cultivars and managements, such as nitrogen (N) fertilisation, based on the assumption that under low yielding conditions modern barley cultivars would not represent a real improvement, and concomitantly their responsiveness to N fertilisation would be negligible under such conditions.

The response of barley cultivars to N fertilisation is especially important to bridge the gap between attainable yield and yield potential (van Ittersum and Rabbinge 1997; Sadras *et al*. 2009). While the last is defined as the productivity of a cultivar grown under an adapted environment without water or N limitations and with control of weeds, plagues and diseases (Evans and Fischer 1999), the former is one achieved under suboptimal conditions of growth due to water or nutritional limitations, which represents a situation broadly extended in agricultural systems (van Ittersum and Rabbinge 1997). The gap between these yield levels can be

reduced through the optimisation of the interaction between cultivars and crop management. This may be particularly important in barley growing systems as this crop has been traditionally cultivated under low yielding environments with a restricted use of inputs.

Effective soil depth, which affects both water availability and nutrient uptake, is an important cause of the gap between attainable yield and yield potential (Sadras and Calviño 2001). Shallow soils accentuate the negative effect of water deficit on yield; however, this response is highly variable within the main barley crop area of Argentina. In this area, shallow soils could also have a detrimental effect on yield stability between years taking into account the sensitivity of yield to rainfall during the crop cycle (Calviño and Sadras 2002). In a context of interannual climate variability, the interaction between cultivar, soil depth and water and N availability makes it difficult to match crop requirements and N supply. The use of crop simulation models constitutes a helpful approach for evaluating crop management practices aimed at optimising crop responses to soil resources. They allow generating information that is difficult, and time consuming, to be acquired by traditional experimentation (Angus *et al.* 1993; Anwar *et al.* 2009). Through the use of simulation models it is possible to assess the effect of water and nutrient availability on crops taking into account the multiple interactions involved in these evaluations (Stapper and Fischer 1990; Savin *et al.* 1995; Ghaffari *et al.* 2001). The analysis of multiannual weather would allow adjusting agricultural management decisions in order to reduce suboptimal conditions as well as to take advantage of favourable rainfall conditions. DSSAT models (Tsuji *et al.* 1994) are one of the most used crop simulation models worldwide. The goodness of the CERES-Barley model has been broadly validated for estimating yield under different conditions around the world (Eitzinger *et al.* 2004; Nain and Kersebaum 2004) as well as in the barley cropping area of Argentina (Travasso and Magrin 1998).

The aim of the present work was to quantify the effect of different N and water availabilities on attainable yield of a traditional and a modern barley cultivar under contrasting soil types using the CERES-Barley simulation model. This would help in (*i*) determining whether the advantage of modern cultivars over their traditional counterparts is restricted to high yielding conditions or in fact expressed under a wide range of yielding conditions, and (*ii*) understanding whether farmers could increase fertilisation levels for modern cultivars.

Materials and methods

In order to achieve the objective, first the performance of the simulation model CERES-Barley 3.5 (Tsuji *et al.* 1994) was assessed for the specific conditions of this study, and then we analysed the response of a traditional and a modern barley cultivar to different combinations of N and water availabilities in a shallow and a deep soil in the south-east of the Buenos Aires province, the main barley production area in Argentina.

Cultivars characterisation and model validation

The cultivars used in the analysis were Malteria Heda (released by Malteria Hudson, Darragueira/Heines Hanna) and B1215 (released by Busch Agricultural Research Inc., Klages/ RPB72–456) as representative of a traditional (i.e. low yield potential) and a modern (i.e. high yield potential) malting barley cultivar, respectively. These cultivars, which had been previously evaluated under field conditions (Abeledo *et al.* 2003*a*, 2003*b*), were chosen as representative of different eras considering their acreage and the period of time under cultivation. Malteria Heda was released to the market in 1944, while B1215 is currently in use. Both cultivars have similar phenology (i.e. time to anthesis or maturity; Abeledo *et al.* 2003*a*) but the modern cultivar has a consistently higher yield potential than the traditional one (Abeledo *et al.* 2003*a*).

CERES-Barley 3.5 characterises cultivars through six genetic coefficients. Three of them are related to phenological behaviour (P1V, vernalisation sensibility; P1D, photoperiod sensibility; P5, grain filling duration) and the other three are related to growth characteristics (G1–G3), accounting for grain number per unit weight of stem-plus-ear at anthesis (G1), grain filling rate (G2), and dry weight of the stem-plus-ear at the end of the stem elongation phase under non-stressed conditions (G3) (Tsuji *et al.* 1994). Genetic coefficients related to phenology and yield of the modern cultivar (B1215) were calculated and validated in previous experiments, in which the cultivar performance was evaluated at four sowing dates: 23 June, 23 August, 22 September and 22 October (Abeledo *et al.* 1999). The calculated coefficients were then validated through an additional independent experiment combining four sowing dates (16 July, 15 August, 14 September and 21 October) and two soil N availabilities at sowing (40 and 120 kg N ha^{-1}; Abeledo *et al.* 1999). The experiments were carried out at the experimental field of the University of Buenos Aires (34°35′S, 58°29′W, altitude 25 m), Argentina.

Genetic coefficients of the traditional cultivar (Malteria Heda) were calculated for the present study by using previously published data (Passarella *et al.* 2003) of experiments sown on 23 June 1999 and 1 August 2000. All experiments were also carried out at the experimental field of the University of Buenos Aires. Before sowing, soil moisture and N content were measured and then plots were fertilised to complement soil mineral N content to a crop N availability at sowing of 120 kg N ha^{-1}.

Model performance for the traditional cultivar was tested with data from two independent experiments carried out in the same experimental field. One of the experiments evaluated Malteria Heda at potential conditions (Abeledo *et al.* 2003*a*), while the other experiment assessed the traditional cultivar under four levels of N availabilities at sowing: 20, 50, 80, 110 and 160 kg N ha^{-1} (for details see Abeledo *et al.* 2003*b*). These experiments were irrigated to avoid water shortage, and biotic stresses (weeds, insects and diseases) were prevented or controlled. Anthesis and maturity dates were recorded in the experiments aimed at both calculating and validating genetic coefficients. At anthesis, aboveground biomass was determined from plants taking a 1-m-long sample within the central row of each plot. The plants were separated into stems, leaves, and spikes. Biomass samples were oven-dried at 65°C for 72 h and weighed. At maturity, plants were cut at ground level and aboveground biomass, yield, grain number per m^2, spikes per m^2, grains per spike and grain weight were measured. Genetic

coefficients were calculated using the GenCalc software through an iterative procedure (Hunt *et al*. 1993).

The performance of the model was assessed by regressing simulated and observed values for anthesis date, maturity date and yield. In addition, the slope of the linear regression relative to the 1 : 1 relationship was estimated as well as the coefficient of determination, the mean bias error, the mean percentage error, and the root mean square error (Bannayan and Crout 1999).

Assessment of cultivar response to different management strategies

Soil types

Management strategies were evaluated at two locations in Southern Buenos Aires province with contrasting dominant soil types: Coronel Suarez (37°26′S, 61°53′W, altitude 233 m) and Tres Arroyos (38°23′S, 60°27′W, altitude 115 m). In both sites soils are mainly Hapludolls but characterised as shallow (0.6 m in Coronel Suarez) or deep (1.4 m in Tres Arroyos) soils (Salazar Lea Plaza and Moscatelli 1989). At each site, 25 years of simulations were performed for the traditional and the modern cultivar assuming 15 July as sowing date and a plant density of 250 pl m^{-2} (both practices are commonly used by farmers in these areas; INTA 1997).

Fallow was simulated in our study taking into account the regular use of this practice in the cropping systems of the studied area. Moreover, the importance of evaluating fallow is highlighted by its likely differential impact on shallow or deep soils. For the simulation proposes, the fallow period was initiated 90 days before sowing assuming sunflower as the previous crop, which is a very common case in reality (INTA 1997; Alberdi and Guyot 2001; González-Montaner 2001). Following Meinke *et al*. (1993) and Dardanelli *et al*. (1997), soil water availability was assumed 10% of field capacity at the beginning of fallow. In addition, we considered a clean fallow, where soil water content during the fallow period was only dependent on rainfall, soil water holding capacity, and soil evaporation variability between years.

Management strategies

A wide range of environmental conditions were simulated, given by the combination of (*i*) different N levels in soil at sowing, and (*ii*) different water conditions both during the fallow period and throughout the crop cycle. For assessing N strategies, nine levels of N availabilities in the soil were simulated by setting initial N at sowing between 20 and 180 kg N ha^{-1} (increased by steps of 20 kg N ha^{-1}, termed as N$_{20}$ to N$_{180}$). The water availability scenarios evaluated in this study were the factorial combination of: (*ii.a*) three fallow conditions (low, intermediate and high rainfall during the fallow period, termed –F, =F and +F, respectively), and (*ii.b*) three conditions during the crop cycle (low, intermediate and high rainfall from sowing to maturity, termed –C, =C and +C, respectively). These scenarios were chosen taking into account 25-year historical records (from 1977 to 2002) for each location. A low rainfall scenario during the fallow period (–F) corresponded to simulations of 20% of the 25 years (i.e. 5 years) with the lowest rainfall during the fallow period. Equivalently, the high rainfall fallow period (+F) corresponded to simulations of 20% of the years with the highest level of rainfall during the fallow period. The intermediate fallow period condition (=F) was calculated by averaging rainfall across the 25 years analysed. Following similar criteria water scenarios during the crop cycle were simulated considering 20% of the years with the lowest (–C) and highest (+C) rainfall from sowing to maturity. The intermediate water condition during the crop cycle (=C) was the average rainfall across the 25 years of simulations. The combination of water conditions during the fallow and the crop cycle allowed us to define nine water scenarios: –F–C, –F=C, –F+C, =F–C, =F=C, =F+C, +F–C, +F=C, and +F+C (Fig. 1). In the context of our work, yield potential of each cultivar for each location was that obtained under the highest water availability condition (+F+C) and with N availability maximised (N$_{180}$), while attainable yields were those obtained in each of the other conditions.

Results

Cultivar characterisation and model performance

Genetic coefficients for phenological traits were similar between cultivars due to the fact that they did not show differences in either anthesis or maturity dates recorded in field experiments (see Abeledo *et al*. 2003*a*). The P1V and P1D coefficients were 0.7 and 4.7, respectively; while the P5 was 2.7 for both cultivars. Main difference between cultivars was found in genetic
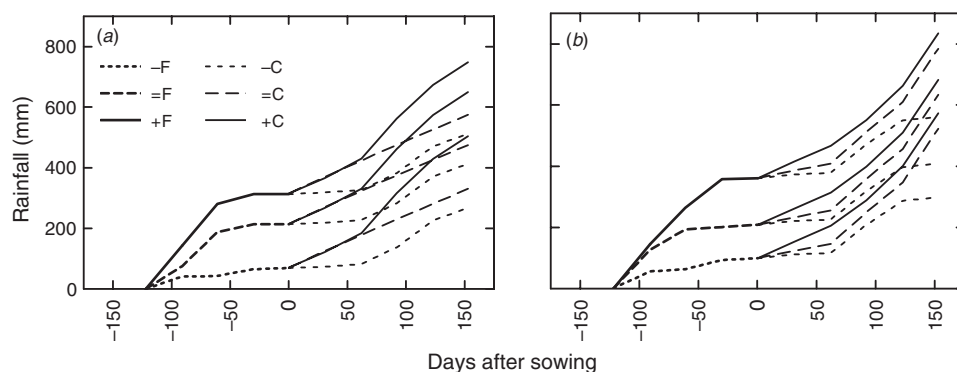

Fig. 1. Rainfall and days after sowing for malting barley crops grown in a shallow (*a*) or a deep soil (*b*) under low (–F), intermediate (=F) or high (+F) rainfall during the fallow period and low (–C), intermediate (=C) or high (+C) rainfall during the crop cycle.

coefficients related to growth and yield determination. The G1 coefficient, accounting for grain number, was 4.5 and 5.0 for the traditional and the modern cultivar, respectively; whereas coefficient G3, the other coefficient that determined grain number, was 0.5 and 4.7, respectively. Finally, G2 (related to grain filling rate) was estimated at 3.2 for the traditional and 5.9 for the modern cultivar.

Validation of the model is shown in Fig. 2 by average values of both observed and simulated data of phenological dates and yield. The CERES-Barley model performance was satisfactory for crop phenology, also achieving a reasonably good performance for yield estimation with a root mean square error of 15% for both cultivars (Fig. 2).

Modelling cultivar yield

The range of anthesis [103–108 days after sowing (DAS)] and maturity date (141–145 DAS) as well as photoperiod before anthesis (12.8 h day^{-1}) explored during the modelling process were within the range of data explored during the validation process. Averaged across years, yield potential under the shallow soil was 5.0 Mg ha^{-1} for the traditional cultivar and 6.0 Mg ha^{-1} for the modern one (with a maximum value of 5.3 and 6.6 Mg ha^{-1}, respectively). In the deeper soil, yield potential averaged 5.1 and 6.1 Mg ha^{-1} for the traditional and the modern cultivar, respectively (with maximums of 5.8 and 7.1 Mg ha^{-1}, respectively). Average attainable yield (i.e. cultivars growing under the =F=C water scenario, with an intermediate soil N content at sowing of 80 kg N ha^{-1}) was 2.1 Mg ha^{-1} in the shallow and 4.0 Mg ha^{-1} in the deep soil for the traditional cultivar; while the modern cultivar reached 2.6 and 4.9 Mg ha^{-1}, respectively. Thus, a clear effect of cultivar was found as the modern cultivar out-yielded the traditional one by ~16% ($P < 0.001$) in both potential and average yielding conditions. In addition, the gap between attainable yield and yield potential was similar between cultivars and only modified by the soil condition; i.e. under the shallow soil the gap between attainable yield and yield potential was 58%, and decreased to 21% in the deeper soil.

Cultivar response to management practices

The response of the cultivars to management practices was remarkably variable between sites and years, with a range of yield explored from 1.2 to 6.1 Mg ha^{-1}. Yield response to improvements in N and water availabilities showed a similar pattern in the traditional and the modern cultivar. Increases in N availability generated, in both cultivars, a gain in attainable yield up to a N level at which yields levelled off (Figs 3 and 4). The soil N level at sowing for achieving maximum yield ranged from 40 to 105 kg N ha^{-1}, depending on cultivar and water availability. As expected, there was a strong positive relationship between the yield level in absence of N stress and the N requirements for reaching that yield (Fig. 5). Interestingly, the N required for levelling off grain yield was slightly higher in the traditional than in the modern cultivar (95 and 85 kg N ha^{-1}, respectively; averaged across the data shown in Fig. 5). N requirements to achieve maximum yield under each water scenario was strongly dependent on the soil type as yield levelled off in the shallow soil with lower N levels (78 and 100 kg N ha^{-1} for the shallow
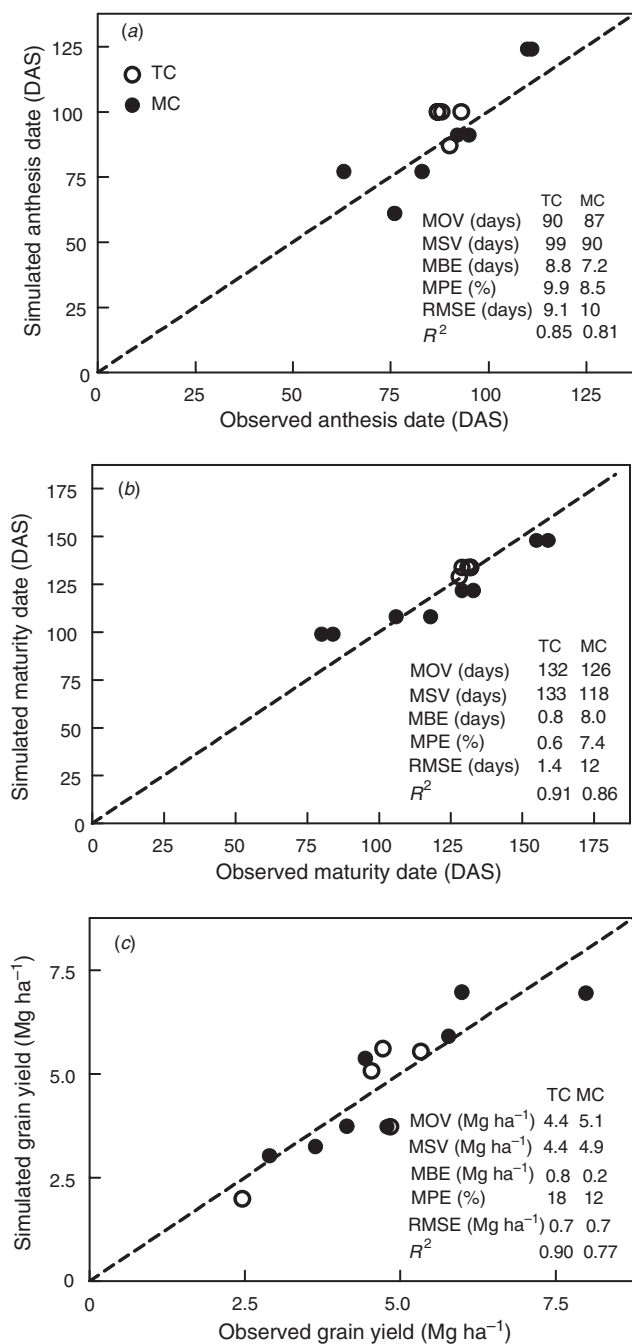

Fig. 2. Model performance between simulated and observed anthesis and maturity dates (days after sowing, DAS), and yield for a traditional (TC) and a modern cultivar (MC) of malting barley. The dotted lines represent the 1:1 ratio. Data values included as text in the figure are the average observed (MOV) and simulated values (MSV), MBE (mean average bias error), MPE (average percentage error), RMSE (root mean square error), and determination coefficient (R^2) of the lineal regression between simulated and observed data.

and deep soils, respectively; Fig. 5). In addition, the N requirement for maximising yield tended to increase ~40 kg N ha^{-1} with increases in the level of rainfall throughout the crop cycle from the –C to the +C condition (it ranged from
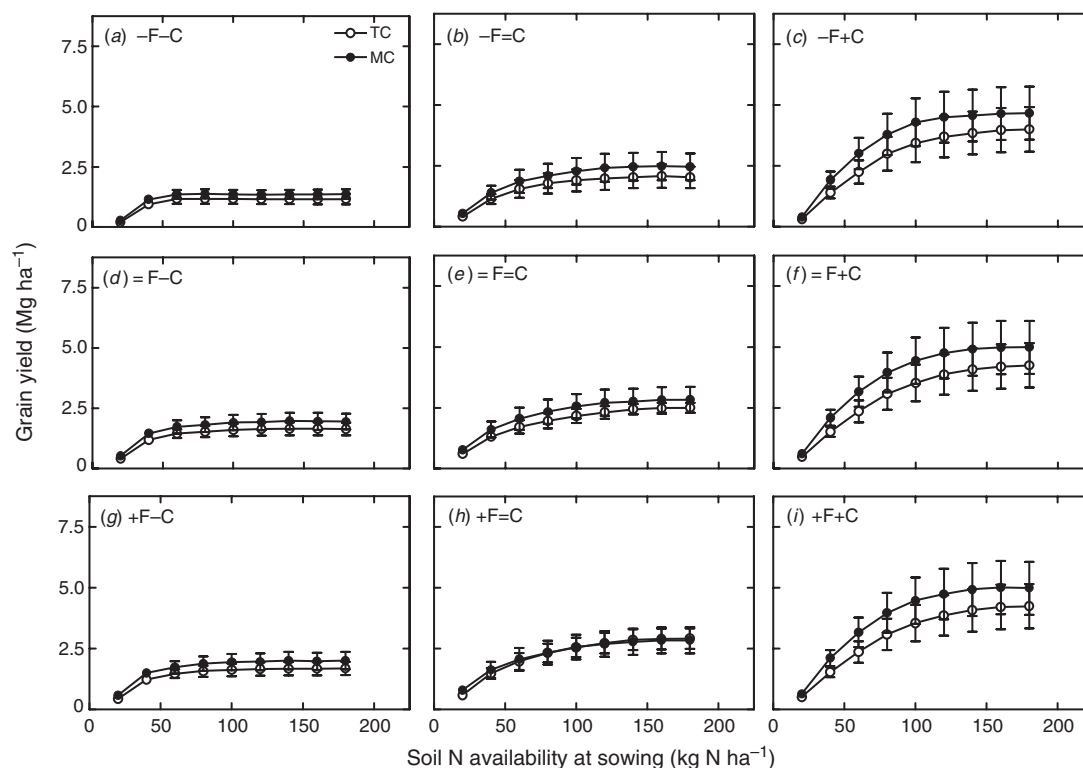
Fig. 3. Yield and soil N availability at sowing for a traditional (TC) and a modern cultivar (MC) of malting barley grown in a shallow soil under low (*a–c*; –F), intermediate (*d–f*; =F) or high (*g–i*; +F) rainfall during the fallow period and low (*a, d, g*; –C), intermediate (*b, e, h*; =C) or high (*c, f, i*; +C) rainfall during the crop cycle. Vertical bars indicate a standard deviation from the means.

65 to 111 kg N ha^{-1}). Increases in the rainfall during the fallow period did also increase N requirement for maximising yield (from 80 kg N ha^{-1} for –F to 95 kg N ha^{-1} for +F).

In order to evaluate the interaction between cultivar and management scenarios, yields were analysed in relative (%) terms to the yield of the modern cultivar growing under the highest water and N availability (+F+C in N$_{180}$; Fig. 6). The yield penalty for using the traditional cultivar instead of the modern one was 20% for the highest yielding condition (+F+C N$_{180}$) in both the shallow and the deep soils, but this difference was reduced to 7% in the lowest yielding condition (–F–C N$_{40}$). Thus, yield of the modern cultivar was higher than (or at least equal to) that of the traditional cultivar independently of the growing condition (i.e. in none of the 81 water by N conditions explored, determining yielding environments from ~1 to over 6 Mg ha^{-1}, the traditional cultivar out-yielded the modern one). Therefore, the modern cultivar showed both higher yield in the poorest growing conditions and higher responsiveness to improvements in the environmental conditions relative to the traditional cultivar (Fig. 6).

Efficiency in the use of resources

Yield advantage of the modern cultivar was based on its higher grain N-use efficiency (NUE$_{grain}$, calculated as the ratio between yield and N availability at sowing). At the soil N availability condition in which yield of each cultivar levelled off, the modern cultivar was more efficient in using N than the traditional cultivar (49 and 37 kg kg N^{-1}, respectively; Fig. 5).

This difference between cultivars in NUE$_{grain}$ was also evident for all the N and water scenarios explored (Fig. 7). Differences in NUE$_{grain}$ between cultivars were modified by the water availability, as NUE$_{grain}$ increased at higher rainfall during the crop cycle in both soils (Fig. 7*a*). In addition, differences between cultivars in NUE$_{grain}$ enlarged with restrictions in N level (Fig. 7*b*). As expected, NUE$_{grain}$ of both cultivars declined with increases in N availability from ~50 to 100 kg kg N^{-1} (Fig. 7*b*).

Discussion

Agriculture consists of optimising productivity per unit land area which is highly influenced by genotype × environment × management interactions (van Ittersum and Rabbinge 1997). However, profitability is at present highly dependent on the sustainability of cropping systems due to the likely negative impact of using high inputs (Fischer 2009; Sadras *et al.* 2009). Therefore, improving the technical, economic and environmental efficiency of cropping systems is worthwhile. To face this request, crop simulation models provide a helpful tool for assessing strategies aimed at optimising crop production. A major objective of breeding programs is to provide farmers with cultivars that out-yield their predecessors not only in experimental networks in which growing conditions are extremely well controlled but actually on farms. In our work, we evaluated yield response of a traditional and a modern barley cultivar under different arrangements of soil N
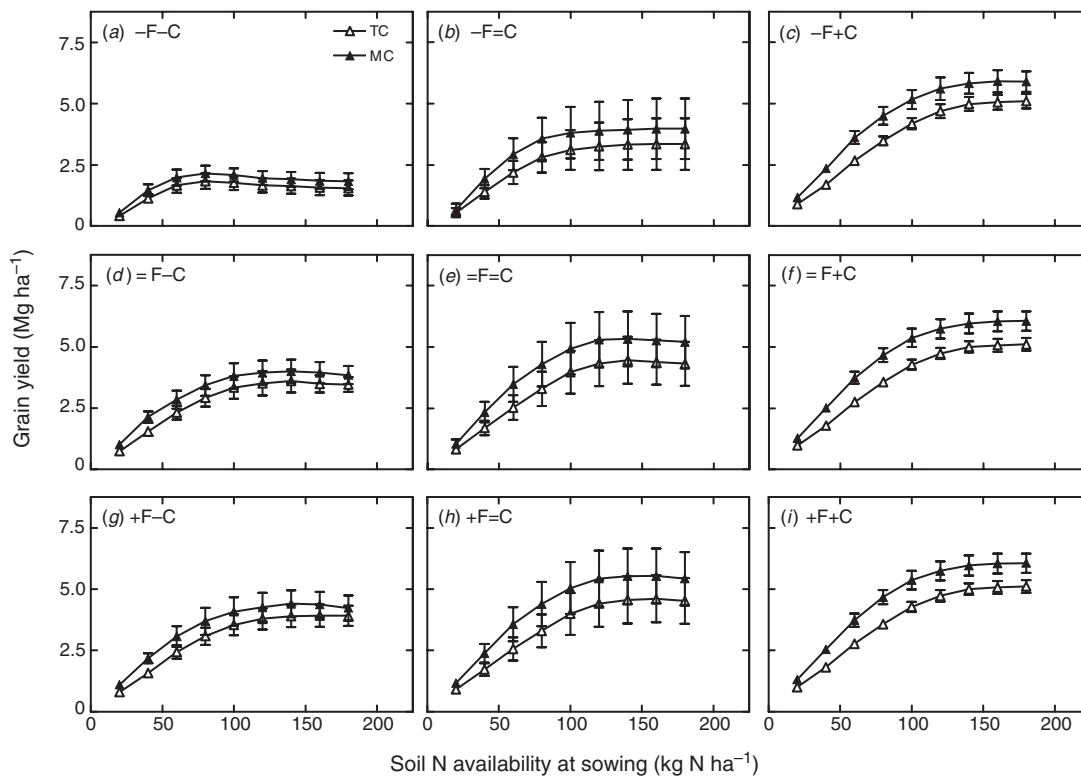
Fig. 4. Yield and soil N availability at sowing for a traditional (TC) and a modern cultivar (MC) of malting barley grown in a deep soil under low (*a–c*; –F), intermediate (*d–f*; =F) or high (*g–i*; +F) rainfall during the fallow period and low (*a, d, g*; –C), intermediate (*b, e, h*; =C) or high (*c, f, i*; +C) rainfall during the crop cycle. Vertical bars indicate a standard deviation from the means.
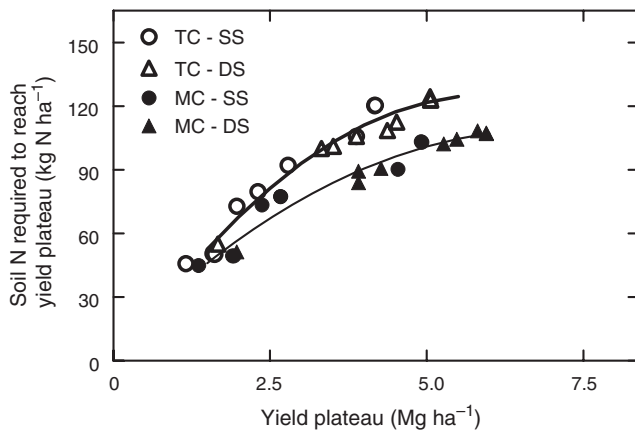

Fig. 5. Soil N required to maximise yield responsiveness to N and maximum yield (yields at the plateau in Figs 3 and 4) for a traditional (TC) and a modern cultivar (MC) of malting barley grown in a shallow (SS) or a deep soil (DS) under different water scenarios. Lines show the fitted equation to the dataset: $y_{TC} = -4.4 + 43.3x - 3.6x^2$ ($R^2 = 0.97$, $P < 0.001$), and $y_{MC} = 6.7 + 29.4x - 2.1x^2$ ($R^2 = 0.95$, $P < 0.001$).

availabilities and water scenarios in a shallow and a deep soil using the CERES-Barley simulation model.

The modern cultivar showed a yield potential ~20% higher than the traditional cultivar (general mean of 6.0 and 5.0 Mg ha^{-1}, respectively), and also higher attainable yields (general mean

difference of 17%). The attainable yield of the cultivars was subordinated to soil type. Averaged across cultivars, attainable yield was 2.3 Mg ha^{-1} in the shallow and 4.4 Mg ha^{-1} in the deep soils. These average attainable yields represented 42% of the yield potential in the shallow and 79% in the deep soil profiles. This agrees with recent results published by Fischer and Edmeades (2010), who highlighted that there is a strong parallelism between potential and attainable yields. Moreover, the gap in the deep soil estimated in the present simulation study was similar to that calculated by Calviño and Sadras (2002) for high yielding modern wheat cultivars in the south-eastern Pampas (25%). The higher gap found in the poorer edaphic condition (shallow soil) is similar to that obtained for wheat crops growing under lower yielding environments such as the Mediterranean region (60%, Abeledo *et al*. 2008).

We found that the modern cultivar performed better than the traditional one under low or high water or N availabilities whatever the site and growing season (Figs 3 and 4). Consequently, although the slope of the relationship between yield and the environmental index was higher ($P < 0.001$) for the modern cultivar, there was no crossover interaction (Fig. 8*a*). The response of the traditional and the modern cultivars found in the present study was contrasted against experimental data reported in the literature (Fig. 8*b*). The studies considered here were those in which yield of cultivars of two-rowed barley released at different eras were assessed under at least three different experimental conditions (Martiniello *et al*. 1987; Muñoz *et al*. 1998; Abeledo *et al*. 2003*b*; Sinebo 2005). In
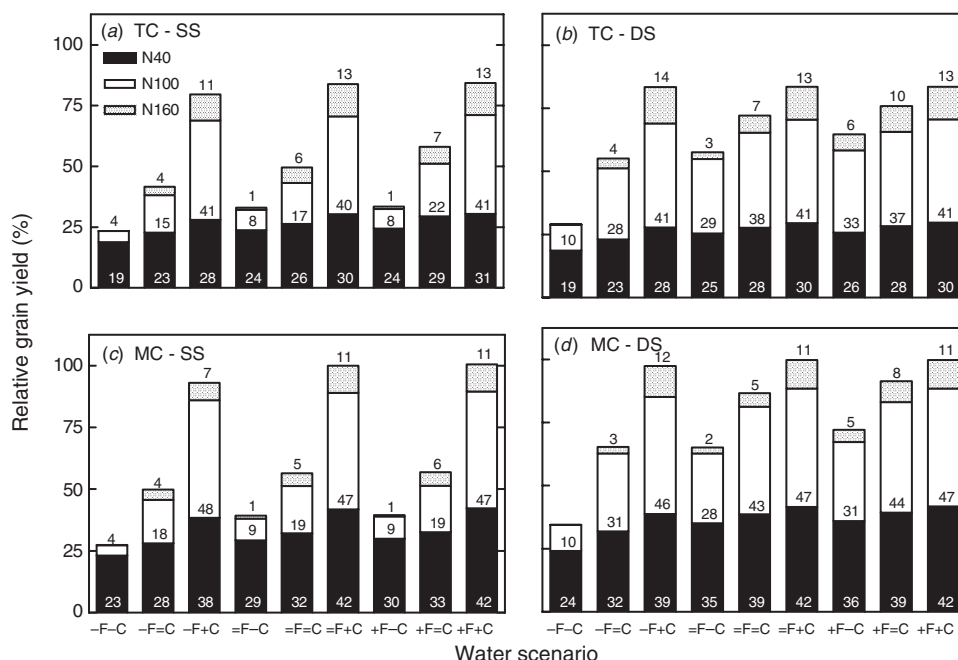
Fig. 6. Accumulated relative yield for a traditional (*a*, *b*; TC) and a modern cultivar (*c*, *d*; MC) of malting barley grown in a shallow (*a*, *c*; SS) or a deep soil (*b*, *d*; DS) under low (–F), intermediate (=F) or high (+F) rainfall during the fallow period and low (–C), intermediate (=C) or high (+C) rainfall during the crop cycle for soil N availabilities at sowing of 40, 100 and 160 kg N ha^{-1}. Yield was expressed in relative terms as a percentage of the yield plateau reached by the modern cultivar growing under the +F+C N$_{180}$ condition within each soil type (yields at the plateau in Figs 3*i* and 4*i*).
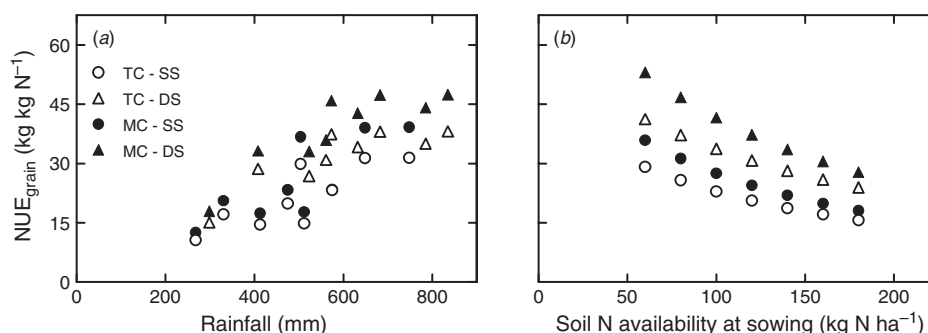

Fig. 7. Grain nitrogen-use efficiency (NUE$_{grain}$, calculated as the ratio between yield and soil N availability at sowing) plotted against either rainfall from the beginning of the fallow period to maturity (*a*), or soil N availability at sowing (*b*) for a traditional (TC) and a modern cultivar (MC) of malting barley grown in a shallow (SS) or deep soil (DS). Values are the averages of N fertilisations (*a*) or rainfall regimes (*b*).

each of these studies we called 'traditional' the cultivar released closest to the mid 1940s (when Malteria Heda was released) and 'modern' the cultivar released in the mid 1990s (when B1215 was released). It is remarkable that, disregarding the large differences between studies, the published data agree with our simulation (i.e. the genotype × environment interaction did not imply a crossover; Fig. 8*b*), and therefore modern cultivars out-yielded traditional ones throughout a rather wide range of growing conditions, including low yielding environments. More remarkable is that the slopes were similar not only between cultivars released in different countries (Argentina,

Ethiopia, Italy and Spain, see references above) but also to our simulations (Fig. 8*b*). The strong parallelism between the results obtained in our study and those from field experiments reported in the literature provides further confidence to our conclusions. Similar findings were accounted for wheat regarding that modern cultivars out-yielded traditional ones across different growing conditions (Ortiz-Monasterio *et al*. 1997; Calderini and Slafer 1999; Guarda *et al*. 2004; De Vita *et al*. 2007; Acreche *et al*. 2008, 2009).

The cultivars largely differed in NUE$_{grain}$, which explained differences in yield between the traditional and the modern
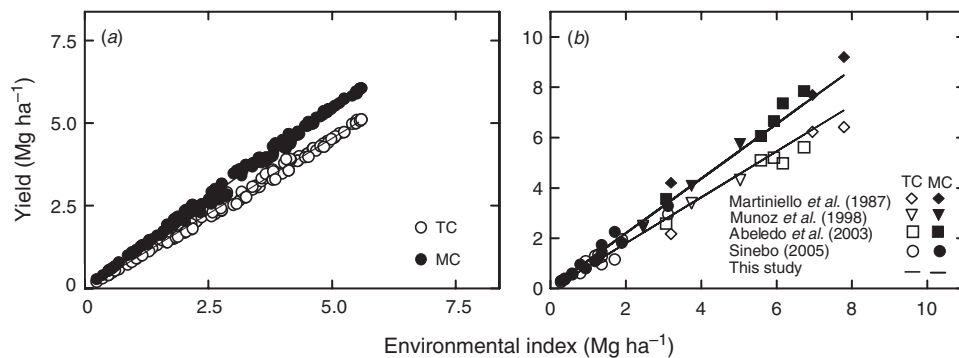
Fig. 8.   Yield and environmental index for the traditional (TC) and the modern cultivar (MC) of malting barley used in the present study (*a*), and for traditional and modern cultivars of barley for data of actual experiments taken from the literature (*b*). For (*b*) the cultivars selected as TC and MC in each article were those with a year of release closest to the TC and MC used in our study, respectively. The environmental index was calculated as the average yield of both categories of cultivars (traditional and modern) in each environment. Lines in (*a*) were fitted by linear regression for the traditional ($y_{TC} = 0.90x - 0.02$, $R^2 = 0.99$, $P < 0.001$) and the modern cultivar ($y_{MC} = 1.09x + 0.02$, $R^2 = 0.99$, $P < 0.001$) categories used in the present study. Lines in (*b*) are not the regressions for the data shown in the panel, but the linear regressions fitted in (*a*).

cultivar as well as their different response to interannual variability. The modern cultivar showed higher NUE$_{grain}$ than the traditional one (Figs 5 and 6). Differences between cultivars in NUE$_{grain}$ were enlarged by environmental conditions, where lower availability of soil N and higher rainfall increased differences between cultivars in NUE$_{grain}$ (Figs 5 and 6). The higher NUE$_{grain}$ shown by the modern cultivar agrees with results from field studies reporting a positive effect of breeding on NUE$_{grain}$ in barley (Abeledo *et al.* 2008) and wheat (Slafer *et al.* 1990; Calderini *et al.* 1995; Ortiz-Monasterio *et al.* 1997; Guarda *et al.* 2004). In addition, N also played a remarkable role in tempering the effect of year-to-year variability on yield. High N availabilities contributed to stabilise yield independently of the water scenario (Figs 3 and 4). However, this has the risk of increasing grain protein concentration, a topic that was not analysed under the context of the present work but that plays a key role in characterising grain quality penalties in malting barley (Savin and Molina-Cano 2002) and profitability of the farmers.

The soil N level required for achieving the maximum yield was higher with increases in rainfall during the pre- as well as the post-sowing period. The positive effect on yield of water accumulated during the fallow was clearly remarkable for deeper soils in low rainfall years (–C treatment) (Fig. 4). These results are consistent with those observed by Savin *et al.* (1995), who reported, for wheat grown in the Pampas, that water stored in the soil during the fallow was relevant only in years with low rainfall during the growing season. Thus, soil water content measured immediately before sowing is an important factor to decide on N fertilisation, as highlighted by Lester *et al.* (2010). Similarly, the effect of rainfall during the crop cycle on yield response to N was important under both soil types, but it tended to be lower in the deeper soil after a rainy fallow period (Figs 3 and 4). This is in agreement with Calviño and Sadras (2002), who showed that wheat yield response to rainfall during the crop cycle was higher in a shallow (depth between 0.5 and 0.7 m) than in a deep soil (depth >1.0 m). It is important to point out that differences in lodging sensitivity

between cultivars or negative effects of extremely high rainfall conditions are not considered by the simulation model. Therefore, these and other constraints would modify the results reported here, but the consistency of the simulated responses with published experimental data of both barley and wheat discussed above, gives strong support to this study, at least for a wide range of environmental conditions faced by farmers in the area under study as well as other barley regions with similar growing conditions.

In conclusion, the modern cultivar achieved, for the whole range of conditions explored, superior yield than the traditional cultivar. Increases in the N availability generated a similar pattern of yield response in both cultivars. However, cultivars differed in the magnitude of the response regarding that the improvement of the environment (i.e. higher N level or higher water availability due to fallow and/or rainfall after sowing) determined consistently higher yield gain in the modern than in the traditional cultivar. Water availability (i.e. rainfall) was the major environmental driver of yield for both cultivars in the shallow as well as in the deep soil but N was also central for reaching high yields, even with restricted water conditions, in line with evidence of improved wheat yields through N fertilisation in low yielding conditions of Australia (Angus 2001; Passioura 2002) and Tunisia (Cossani *et al.* 2011). The modern cultivar showed higher NUE$_{grain}$ than the traditional cultivar, and the low soil N availability and high rainfall condition highlighted NUE$_{grain}$ differences between cultivars. Farmers would face little risk in adopting higher yielding cultivars, in both high and low yielding environments, and would benefit from N fertilising their crops in most years.

References

Abeledo LG, Calderini DF, Miralles DJ, Dreccer MF (1999) Generation and validation of the genetic coefficients of two and six-rowed barley cultivars for the CERES-Barley simulation model. III Congreso Latinoamericano de Cebada (Barley Latin-America Congress). [In Spanish] (Eds S Germán, S Stewart, A Peculio, J Elizondo, F Gamba, I González, E Ordoqui, D Luizzi, D Musetti) pp. 77. (Mesa Nacional de Entidades de Cebada Cervecera: Colonia)

Abeledo LG, Calderini DF, Slafer GA (2003a) Genetic improvement of barley yield potential and its physiological determinants in Argentina (1944–1998). *Euphytica* **130**, 325–334. doi:10.1023/A:1023089421426

Abeledo LG, Calderini DF, Slafer GA (2003b) Genetic improvement of yield responsiveness to nitrogen fertilization and its physiological determinants in barley. *Euphytica* **133**, 291–298. doi:10.1023/A:1025796527208

Abeledo LG, Calderini DF, Slafer GA (2008) Nitrogen economy in old and modern malting barleys. *Field Crops Research* **106**, 171–178. doi:10.1016/j.fcr.2007.11.006

Acreche M, Briceño-Félix G, Martín Sánchez JA, Slafer GA (2008) Physiological bases of genetic gains in Mediterranean bread wheat yield in Spain. *European Journal of Agronomy* **28**, 162–170. doi:10.1016/j.eja.2007.07.001

Acreche M, Briceño-Félix G, Martín Sánchez JA, Slafer GA (2009) Grain number determination in an old and a modern Mediterranean wheat as affected by pre-anthesis shading. *Crop & Pasture Science* **60**, 271–279. doi:10.1071/CP08236

Alberdi JI, Guyot F (2001) Modelos de Producción de trigo en regiones CREA. Región Sudoeste. In 'Trigo. Cuaderno de Actualización Técnica CREA No. 63'. (Ed. EH Satorre) pp. 119–122. (Área de Comunicaciones de AACREA: Buenos Aires)

Angus JF (2001) Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture* **41**, 277–288. doi:10.1071/EA00141

Angus JF, Bowden JW, Keating BA (1993) Modelling nutrient responses in the field. *Plant and Soil* **155–156**, 57–66. doi:10.1007/BF00024984

Anwar MR, O'Leary GJ, Rab MA, Fisher PD, Armstrong RD (2009) Advances in precision agriculture in south-eastern Australia. V. Effect of seasonal conditions on wheat and barley yield response to applied nitrogen across management zones. *Crop & Pasture Science* **60**, 901–911. doi:10.1071/CP08351

Bannayan M, Crout NMJ (1999) A stochastic modelling approach for real-time forecasting of winter wheat yield. *Field Crops Research* **62**, 85–95. doi:10.1016/S0378-4290(99)00008-8

Bell MA, Fischer RA, Byerlee D, Sayre K (1995) Genetic and agronomic contributions to yield gains: a case study for wheat. *Field Crops Research* **44**, 55–65. doi:10.1016/0378-4290(95)00049-6

Brancourt-Hulmel M, Heumez E, Pluchard P, Beghin D, Depatureaux C, Giraud A, Le Gouis J (2005) Indirect versus direct selection of winter wheat for low-input or high-input levels. *Crop Science* **45**, 1427–1431. doi:10.2135/cropsci2003.0343

Calderini DF, Slafer GA (1999) Has yield stability changed with genetic improvement of wheat yield? *Euphytica* **107**, 51–59. doi:10.1023/A:1003579715714

Calderini DF, Torres-León S, Slafer GA (1995) Consequences of wheat breeding on nitrogen and phosphorus yield, grain nitrogen and phosphorus concentration and associated traits. *Annals of Botany* **76**, 315–322. doi:10.1006/anbo.1995.1101

Calviño P, Sadras V (2002) On-farm assessment of constraints to wheat yield in the south-eastern Pampas. *Field Crops Research* **74**, 1–11. doi:10.1016/S0378-4290(01)00193-9

Ceccarelli S, Grando S, Bailey E (2001) Farmer participation in barley breeding in Syria, Morocco and Tunisia. *Euphytica* **122**, 521–536. doi:10.1023/A:1017570702689

Cossani CM, Thabet C, Mellouli HJ, Slafer GA (2011) Improving wheat yields through N fertilization in Mediterranean Tunisia. *Experimental Agriculture* (In press).

Dardanelli JL, Bachmeier OA, Sereno R, Gil R (1997) Rooting depth and soil water extraction patterns of different crops in a silty loam Haplustoll. *Field Crops Research* **54**, 29–38. doi:10.1016/S0378-4290(97)00017-8

De Vita P, Li Destri Nicosia O, Nigro F, Platani C, Riefolo C, Di Fonzo N, Cattivelli L (2007) Breeding progress in morpho-physiological, agronomical and qualitative traits of durum wheat cultivars released in Italy during the 20th century. *European Journal of Agronomy* **26**, 39–53. doi:10.1016/j.eja.2006.08.009

Eitzinger J, Trnk M, Hösch J, Žalud M, Dubrovský M (2004) Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. *Ecological Modelling* **171**, 223–246. doi:10.1016/j.ecolmodel.2003.08.012

Evans LT, Fischer RA (1999) Yield potential: its definition, measurement, and significance. *Crop Science* **39**, 1544–1551. doi:10.2135/cropsci1999.3961544x

FAO (2010) Food and Agriculture Organization of the United Nations. World Agricultural Information Centre, Agriculture data. Available at: www.fao.org/ (accessed 16 March 2011)

Fischer RA (2009) Farming systems of Australia: exploiting the synergy between genetic improvement and agronomy. In 'Crop physiology: applications for genetic improvements and agronomy'. (Eds V Sadras, DF Calderini) pp. 23–54. (Elsevier: Amsterdam)

Fischer RA, Edmeades GO (2010) Breeding and cereal yield progress. *Crop Science* **50**, S85–S98. doi:10.2135/cropsci2009.10.0564

Ghaffari A, Cook HF, Lee HC (2001) Simulating winter wheat yields under temperate conditions: exploring different management scenarios. *European Journal of Agronomy* **15**, 231–240. doi:10.1016/S1161-0301(01)00111-3

González-Montaner J (2001) Modelos de Producción de trigo en regiones CREA. Región Mar y Sierras. In 'Trigo. Cuaderno de Actualización Técnica CREA No. 63'. (Ed. EH Satorre) pp. 119–122. (Área de Comunicaciones de AACREA: Buenos Aires)

Guarda G, Padovan S, Delogu G (2004) Yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels. *European Journal of Agronomy* **21**, 181–192. doi:10.1016/j.eja.2003.08.001

Hunt LA, Pararajasingham S, Jones JW, Hoogenboom G, Imamura DT, Ogoshi RM (1993) GENCALC: software to facilitate the use of crop models for analyzing field experiments. *Agronomy Journal* **85**, 1090–1094. doi:10.2134/agronj1993.00021962008500050025x

INTA (1997) 'Guía práctica para el cultivo de Trigo. Campaña 1997.' (Instituto de Tecnología Agropecuaria. Secretaría de Agricultura, Ganadería, Pesca y Alimentación. Ministerio de Economía y Obras y Servicios Públicos: Buenos Aires)

Lester DW, Birch CJ, Dowling CW (2010) Fertiliser N and P application on two Vertosols in north-eastern Australia. 3. Grain N uptake and yield by crop/fallow combination, and cumulative grain N removal and fertiliser N recovery in grain. *Crop & Pasture Science* **61**, 24–31. doi:10.1071/CP09106

Martiniello P, Delogu G, Oboardi M, Boggini G, Stanca AM (1987) Breeding progress in grain yield and selected agronomic characters of winter barley (*Hordeum vulgare* L.) over the last quarter of a century. *Plant Breeding* **99**, 289–294. doi:10.1111/j.1439-0523.1987.tb01184.x

Meinke H, Hammer GL, Want P (1993) Potential soil water extraction by sunflower on a range of soils. *Field Crops Research* **32**, 59–81. doi:10.1016/0378-4290(93)90021-E

Muñoz P, Voltas J, Araus JL, Igartua E, Romagosa I (1998) Changes over time in the adaptation of barley releases in north-eastern Spain. *Plant Breeding* **117**, 531–535. doi:10.1111/j.1439-0523.1998.tb02202.x

Nain AS, Kersebaum KC (2004) Calibration and validation of CERES model for simulating. In 'Modelling water and nutrient dynamics in soil-crop systems'. (Eds KC Kersebaum, JM Hecker, W Mirschel, M Wegehenkel) pp. 161–181. (Springer: Dordrecht, The Netherlands)

Ortiz-Monasterio JI, Sayre KD, Rajaram S, McMahom M (1997) Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. *Crop Science* **37**, 898–904. doi:10.2135/cropsci1997.0011183X003700030033x

Passarella VS, Savin S, Abeledo LG, Slafer GA (2003) Malting quality as affected by barley breeding (1944–1998) in Argentina. *Euphytica* **134**, 161–167. doi:10.1023/B:EUPH.0000003832.21034.90

Passioura JB (2002) Environmental biology and crop improvement. *Functional Plant Biology* **29**, 537–546. doi:10.1071/FP02020

Pswarayi A, van Eeuwijk FA, Ceccarelli S, Grando S, Comadran J, Russell JR, Francia E, Pecchioni N, Destri OL, Akar T, Al-Yassin A, Benbelkacem A, Choumane W, Karrou M, Ouabbou H, Bort J, Araus JL, Molina-Cano JL, Thomas WTB, Romagosa I (2008) Barley adaptation and improvement in the Mediterranean basin. *Plant Breeding* **127**, 554–560. doi:10.1111/j.1439-0523.2008.01522.x

Sadras VO, Calderini DF, Connor D (2009) Sustainable agriculture and crop physiology. In 'Crop physiology. Applications for genetic improvement and agronomy'. (Eds VO Sadras, DF Calderini) pp. 1–20. (Academic Press: Burlington)

Sadras VO, Calviño PA (2001) Quantification of grain yield response to soil depth in soybean, maize, sunflower, and wheat. *Agronomy Journal* **93**, 577–583. doi:10.2134/agronj2001.933577x

Salazar Lea Plaza JC, Moscatelli G ((1989)) 'Mapa de suelos de la provincia de Buenos Aires. Escala 1 : 500 000.' (Secretaría de Agricultura, Ganadería y Pesca, Instituto Nacional de Tecnología Agropecuaria: Buenos Aires)

Savin R, Molina-Cano JL (2002) Changes in malting quality and its determinants in response to abiotic stresses. In 'Barley: recent advances from molecular biology to agronomy of yield and quality'. (Eds GA Slafer, JL Molina-Cano, R Savin, JL Araus, I Romagosa) pp. 523–550. (Food Product: New York)

Savin R, Satorre EH, Hall AJ, Slafer GA (1995) Assessing strategies for wheat cropping in the monsoonal climate of the Pampas using the CERES-Wheat simulation model. *Field Crops Research* **42**, 81–91. doi:10.1016/0378-4290(95)00029-P

Sinebo W (2005) Trade off between yield increase and yield stability in three decades of barley breeding in a tropical highland environment. *Field Crops Research* **92**, 35–52. doi:10.1016/j.fcr.2004.08.009

Slafer GA, Andrade FH, Feingold SE (1990) Genetic improvement of bread wheat (*Triticum aestivum* L.) in Argentina: relationships between nitrogen and dry matter. *Euphytica* **50**, 63–71. doi:10.1007/BF00023162

Slafer GA, Satorre EH, Andrade FH (1994) Increases in yield in bread wheat from breeding and associated physiological changes. In 'Genetic improvement of field crops'. (Ed. GA Slafer) pp. 1–68. (Marcel Dekker: New York)

Stapper M, Fischer RA (1990) Genotype, sowing date and plant spacing influence on high-yielding irrigated wheat in southern New South Wales. III. Potential yields and optimum flowering dates. *Australian Journal of Agricultural Research* **41**, 1043–1056. doi:10.1071/AR9901043

Tambussi EA, Nogues E, Ferrio P, Voltas J, Araus JL (2005) Does higher yield potential improve barley performance in Mediterranean conditions? A case study. *Field Crops Research* **91**, 149–160. doi:10.1016/j.fcr.2004.06.002

Travasso MI, Magrin GO (1998) Utility of CERES-Barley under Argentine conditions. *Field Crops Research* **57**, 329–333. doi:10.1016/S0378-4290(98)00079-3

Tsuji GY, Jones JW, Balas S (1994) 'DSSAT version 3.' (University of Hawaii: Honolulu)

van Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input–output combinations. *Field Crops Research* **52**, 197–208. doi:10.1016/S0378-4290(97)00037-3