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Best management practices of tillage and nitrogen fertilization in Mediterranean rainfed conditions: combining field and modelling approaches

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Abstract

In this work, appropriate management practices for crop production under the variable climate conditions of the Mediterranean region, in particular rainfall, were tested with the use of a modelling system applied to long-term (i.e. 18 years) field data. The calibration of the CropSyst model was performed using data collected from 1996 to 1999 at three different Mediterranean locations (i.e., HYP-Guissona, MYP-Agramunt and LYP-Candasnos, i.e. high, medium and low yield potential, respectively) within a degree of yield potential. The model simulated reasonably well barley growth and yield to different tillage and N fertilization strategies.

Simulations of barley performance over 50 years with generated weather data showed that yields were often greater and never smaller under no-tillage compared to conventional tillage with a mean increase of 36%, 63% and 18% for HYP-Guissona, MYP-Agramunt and LYP-Candasnos. In MYP-Agramunt, the long-term data showed a 40% increase in grain yields when using no-tillage compared to conventional tillage, as an average of 18 years.

The model also predicted that greater N applications in no-tillage were appropriate to take advantage of additional water supply. Taking into account the limited amount of soil water available, overall N fertilizer applications could be reduced to about half of the traditional rate applied by the farmers without yield loss. The 50-yr simulation, confirmed by the long-term experimental data, identified no-tillage as the most appropriate tillage practice for the rainfed Mediterranean areas. Also, N fertilization must be reduced significantly when tillage is used or when increasing aridity. Our work demonstrates the usefulness of the combination of long-term field experimentation and modelling as a tool to identify the best agricultural management practices. It also highlights the importance of posterior analysis with long-term observed field data to determine the performance of simulation results.

Keywords

Conservation tillage; nitrogen fertilization; crop simulation; CropSyst model.

1. Introduction

In the semiarid Mediterranean region of the Ebro river valley (northeast Spain), dryland agriculture is based on continuous cropping of winter cereals (mainly barley and wheat). In these areas, rainfall is usually low and erratic with significant high evapotranspiration rates. These typical climate characteristics constrain crop productivity due to the shortage of available water during prolonged periods (Austin et al. 1998; Ryan et al. 2006). Consequently, attending to these highly variable climatic conditions, it is difficult to recommend suitable agronomic strategies (Stewart and Robinson 1997, Giambalvo et al. 2014) and specially based on short-term experimentation (Peterson et al. 2011).

Two management practices, tillage and nitrogen (N) fertilization are, however, appropriate targets to improve profitability and reduce environmental impacts of cropping practices. First, they are important determinants of crop yield and are suitable technologies to be developed in Mediterranean areas (Cantero-Martínez and Gabiña, 2004; Ryan et al. 2009). As inputs, they account for more than 40-50% of the cost of crop production (Cantero-Martínez et al. 1995a). Second, the major environmental challenges in the region are to reduce soil erosion (Grove 1996) and N losses (Ryan et al. 2009). Reduced and no-tillage were introduced in the area 35 years ago, with evident success in controlling erosion but with limited acceptance by farmers since its adoption requires confidence in the long-term performance of the system, including adjustment of N fertilization due to modifications in the water and nitrogen balances (Moreno et al. 2010). According to this last, Pittelkow et al. (2014) stated in a meta-analysis the importance and interest of those soil management systems and the need to determine locally their suitability.

Few years ago, the impact of tillage and N fertilization management on crop performance was analysed in Mediterranean dryland conditions (Cantero-Martínez et al. 2003; Angás et al. 2006; Morell et al. 2011). Though these studies provided valuable observed data during three growing seasons, the conclusions and recommendations obtained were taken with caution. The short length of the experimental period (only three growing seasons) limited the possibility of obtaining robust conclusions in these areas with highly-variable climate conditions, making difficult the establishment of appropriate cropping strategies with only few years of experimental data. According to this, in dryland Mediterranean conditions, strong recommendations for crop management would require a large number of experimental years with time and cost associated. The combination of experimental work with the use of crop simulation models may help to overtake this limitation. Crop simulation models that integrate the effects of crop, environment and management to predict crop yield can be used to evaluate different management options over long periods using historical or generated weather data. When evaluated over the long term, crop models can be used to build probability graphs to assess technology options and to analyse their interactions regarding the productivity and sustainability of agricultural systems.

CropSyst (Stöckle and Nelson 1998) is a crop model suitable for simulating yield, taking into account crop characteristics and the relevant crop and soil processes. CropSyst includes ClimGen that is a complement which is able to generate long-term daily weather data by reproducing the observed variability in short-term climate data (Acutis et al. 1999). CropSyst and Climgen have been successfully used for various crop-environment combinations in semiarid conditions, e.g. Pala et al. (1996) for durum wheat in northern Syria (3 years simulation), Donatelli et al. (1997) for crop rotations at two locations in Italy (6 years simulation), Ferrer-Alegre et al. (1999) for irrigated corn in the Ebro river valley in Spain (30 years simulation), Marcos et al. (1999) for a number of crops in dryland conditions in the western United States (2 years simulation), Díaz-Ambrona et al. (1999) for a winter cereal-legumes rotation in the central dryland area of Spain (15 years simulation), and Sadras (2002) in southern Australia to evaluate the problem of terminal drought during grain filling (40 years simulation). All of them with moderate success in the performance of the CropSyst model, but no previous attempt has been made to use CropSyst to predict crop yield under different tillage and N fertilization strategies in this Mediterranean conditions.

The objectives of this work were: (i) to evaluate the ability of the CropSyst model to simulate growth, yield and water use in a barley monocropping dryland system under various tillage and N fertilization regimes; and (ii) to analyse the best tillage and N fertilization combinations that might form the basis of recommended long-term cropping strategies in Mediterranean dryland areas.

2. Materials and Methods

2.1 Location and selected sites

The Ebro river valley (about 40.000 km^2) is a wide region in northeast Spain, highly representative of the arid and semiarid Mediterranean area. Mean annual rainfall ranges from 250 to 500 mm, 60% of which occurs between September and January. Generally, soils are loamy and clay loamy with available soil water capacity ranging between 80 and 250 mm depending on site and soil depth. Mean annual air temperature ranges between 13.0 and 14.5 ºC.

In this study, three sites located within the Ebro river valley were selected. These three sites covered the main climate and soil conditions of the area. They represented the major cropping systems in the region covering the gradient of yield potential of the area.

2.2 Field experiments

Experimental data from three field experiments and three growing seasons (i.e., 1996-1999) were used to evaluate the performance of the model. A detailed description of the field experiments, their agronomic evaluation and the physical and chemical characteristics of the soils were provided in Cantero-Martínez et al. (2003). The three experimental fields were established in 1996. Briefly, field experiments were located at Guissona (41º46'N, 1º16'E, 490 m.a.s.l), Agramunt (41º48'N, 1º07'E, 330 m.a.s.l) and Candasnos (41º30'N, 0º08'E, 280 m.a.s.l), which vary in the amount of rainfall and water holding capacity of their soils, representing a decreasing gradient of yield potential (Table 1). According to this gradient, Guissona, Agramunt and Candasnos were considered as representative sites of high (HYP), medium (MYP) and low (LYP) yield potential, respectively. The experimental field located in Agramunt was maintained under the same conditions and with the same treatments until the 2013-2014 growing season. The 18-year dataset of the Agramunt experiment was used to evaluate the ability of the model as a decision tool for management practices over the long-term.

In all three experimental fields, three tillage systems (i.e., conventional tillage, CT; minimum tillage, MT, and no-tillage, NT) and three mineral N fertilization rates were tested. The three N fertilization rates consisted in high (150, 120 and 100 kg N ha^{-1}), medium (75, 60 and 50 kg N ha^{-1}), and control (no N applied) rates at HYP, MYP and LYP locations, respectively. On each area, the traditional N fertilizer rates applied by farmers correspond to the high rates tested in the corresponding field experiment. Pre-sowing applications were carried out with ammonium sulphate while ammonium nitrate was used at tillering. For this study, only CT and NT treatments were considered. The CT treatment consisted of one mouldboard plow pass (25-30 cm depth) plus one or two cultivator passes (15 cm depth) before sowing, during August and September depending on soil moisture. In the NT treatment, sowing was performed by direct drilling after spraying with herbicide (1.5 L 36% glyphosate [N-(phosphonomethyl)-glycine] plus 1 L of 40% MCPA (2-(4-chloro 2-metilfenoxi) acetic acid) per ha). In the CT treatment and at all three sites, crop residues were incorporated into the soil with tillage operations and the soil remained bare after tillage. Under NT, crop residues were maintained throughout the study period, and at MYP and LYP locations stubble was left and straw was chopped and spread on the soil. At HYP, however, due to the high amount of crop residues, the stubble was left but the straw was removed after harvest in order to facilitate the establishment of the next crop. Daily maximum and minimum temperatures and rainfall were collected from the nearest weather stations (1 to 6 km far) of the National Weather Institute of Spain (INM). Representative soil data from the upper 25 cm layer used for the simulations are shown in Table 1. Stoniness (30%) was taken into account at LYP location to calculate the actual soil water content.

2.3 Overview of the CropSyst model and its evaluation

The version 4.09.01 of the CropSyst model (Stöckle and Nelson, 1998), which includes modules for soil water and nitrogen balances, crop phenology, root growth, leaf area index, biomass and yield, crop residue decomposition and soil erosion, was used for this analysis. The CropSyst model simulates the performance of individual crops or crop rotations, and it was developed as a tool for predicting the effect of management practices on crop production and the environment (Donatelli et al. 1997; Stöckle and Nelson 1998). The model requires inputs of daily climate data, soil type and information about crop management such as N fertilization, irrigation, crop type, cultivar, tillage, and residue management. Crop phenology is simulated by air temperature and photoperiod. The model simulates light and water effects on crop growth based on the radiation and transpiration-use-efficiency concepts (Monteith 1977; Tanner and Sinclair 1983). Calculations of soil water content are the result of the water balance including evaporation, transpiration and runoff and drainage components. Potential evapotranspiration was calculated by the Priestley-Taylor (P-T) equations. Total solar radiation was estimated from the air temperature (Bristow and Campbell 1984). The value for the aridity factor (used to correct the constant that computes maximum daylight vapour pressure deficit) was set to 0.04. The value for the P-T constant (which is a proportionality factor that compensates for the elimination of the aerodynamic component of the Penman Montheith model) was set to 1.35 (Ferrer-Alegre et al. 1999). Soil moisture and soil temperature are considered by the model to calculate a daily soil organic matter decomposition rate.

The model was adjusted through a non-dimensional parameter between 0.6 to 1.8 depending on the tillage treatment and site. For estimations in the model, a complete recharge of the soil water content at field capacity in the winter of the first growing season was considered (Cabalguenne and Debaeke 1995). The model estimates grain yield through the harvest index that is responsive to water stress.

The model was parameterized using the published data in Cantero-Martínez et al. (2003) and Angás et al. (2006) for the NT and CT treatments and high and low N fertilization rates during the 1996 to 1999 period. Table 2 lists the selected values of different crop parameters after the parameterization process and for each experimental field. In most cases, the parameters were estimated from phenological and physiological data of the cultivars collected in the experiments (i.e. crop development, biomass accumulation, time course of leaf area index, and yield components).

The performance of the model was evaluated with the calculation of the relative root mean square error (rRMSE), the mean deviation (MD) and its efficiency (EF):

$$\mathrm{rRMSE} = \frac{100}{\overline{\mathrm{O}}}\sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{S_i}-\mathrm{O_i})^2}$$

$$\mathrm{MD} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{S_i}-\mathrm{O_i})$$

$$\mathrm{EF} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{O_i}-\overline{\mathrm{O}}_\mathrm{i})^2 - \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{S_i}-\mathrm{O_i})^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{O_i}-\overline{\mathrm{O}}_\mathrm{i})^2}$$

Where n is the number of observations, S_i and O_i are the simulated and the observed values, respectively and $\overline{\mathrm{O}}$ is the mean of the observed values.

2.4 Fifty-year simulation and long-term assessment

After model parameterization and evaluation, CropSyst was used to simulate 50 growing seasons of barley continuous cropping for each site without yearly re-initialization. The ClimGen weather generator was tuned with the available weather data for the three sites (i.e., 25 years for the MYP site and 15 years for both HYP and LYP sites) and then used to generate 50 years of weather data for each of the three sites. For the three locations, soil characteristics were the same as those used when validating the model. Initial soil mineral nitrogen and soil water content were the same for all tillage and N fertilizer treatments, but varied for locations, being set to the average of the measurements at the beginning of each experiment. To run the long-term simulation, sowing was fixed on November 1st, which represents the average of the traditional range of sowing dates in the area. The date of N fertilizer application was set equally for all three locations (October 8th for pre-sowing applications and February 15th for top-dressing N application at tillering). Nitrogen losses as ammonia volatilization and nitrate leaching were calculated by the model. Ammonia losses were considered the same for both tillage systems. Mouldboard plowing was dated at September 1st and cultivator tillage at September 21st. For the long-term simulation, crop yield, biomass, soil water content, crop water use (WU) and water-use efficiency (WUE) were analysed. To assess the performance of each technological practice (tillage and N fertilizer rate), the cumulative probability expressed as the probability of exceeding the crop yield was calculated (Cantero-Martínez et al. 1995b). Experimental data measured in the MYP field experiment, which was maintained for 18 years (until the 2013-14 season), was used to compare and assess the 50-year simulation with the measured data through the cumulative probability curves.

3. Results

3.1 Model evaluation

Model performance evaluated through the EF statistic reached 0.71, 0.75 and 0.46 for soil water content, aerial biomass and grain yield, respectively. For the same variables, rRMSE was 24, 41 and 43%, respectively. MD was 0.005 m^3 m^{-3} for soil water content and 274.8 and 39.6 kg dry matter ha^{-1} for the aerial biomass and grain yield, respectively (Table 3).

At the HYP site, crop biomass in the unfertilized treatment was underestimated during the second year in NT and during the second and third years in CT (Fig. 1). At this HYP site, in general, crop biomass values predicted by the model for NT were close to the observed values. However, the model underestimated crop biomass in the CT treatments (Fig. 1). During the 1998-1999 season (i.e., 900 days after the first sowing), the model overestimated the effect of drought, when annual rainfall was an 18% lower than the annual average (i.e. 475 mm). This trend was particularly significant in the CT treatments (Fig. 1). Contrarily, during the three growing seasons, the model simulated acceptably well crop biomass at the MYP location for all fertilization treatments, and only in CT, biomass was underestimated by 10 % at the end of each growing season. At LYP, the model performed well for CT but was not able to simulate the negative effect of pests on biomass growth the last two years in NT (Fig. 1). Leaf area index (data not shown) was simulated less accurately than biomass, and was overestimated by 10-15 % in the N fertilized treatments and by 40-50% under no fertilized treatments.

During the three studied years, simulated values for soil water content (SWC) agreed reasonably well with observed values (Fig. 2). Two exceptions were observed. First, on day 400 after first sowing, at HYP in NT0, simulated SWC was lower than observed values. This time period corresponded to the summer of 1997 when wet conditions resulted in the rapid growth of weeds. The second exception was at HYP in CT0 in which predicted total SWC was underestimated from day 600 to the end of the cropping season. In this treatment, the model simulated high evaporation rates in the shallow soil layer leading to the underestimation of total SWC with values below wilting point. The significant low SWC simulated in the HYP CT0 treatment affected the crop biomass predicted (Fig. 1). In general, at LYP and in both NT0 and CT0, the model overestimated SWC up to 15 % with higher differences between observed and simulated values in NT than in CT.

In general, the CropSyst model simulated reasonably well crop yield (Table 3) with a deviation lower than 15% (Fig. 3). Some exceptions occurred such as the last simulated year (i.e., 1999) in which the model greatly underestimated crop yield. In the LYP site, yield was optimally simulated in CT but in NT the model overestimated crop yield about 30% (Fig. 3).

3.2 Long-term simulation

The results of 50-year simulation with CropSyst showed differences in crop yield and water use among tillage systems and N fertilization rates (Fig. 4).

At the HYP site, for any level of water used, higher crop yields were simulated in NT than in CT (Fig. 4). The predicted average yield was 37% higher under NT than under CT, and more than 50% higher if only N fertilized treatments were considered (Fig. 5). For this site and according to the model, there was no response to N fertilization under CT, but a positive response for NT (from 0 to 75 kg N ha^{-1}). At this location, the probability of obtaining a given crop yield was always higher in NT than in CT (Fig. 6). At the MYP site, in the range of 200 to 300 mm of water used, the model predicted the greatest crop yield under NT. However, when water use increased to 350-

400 mm differences between NT and CT were reduced (Fig. 4). Average yields were 63% higher in NT than under CT and 89% higher if only N fertilized treatments were considered (Fig. 5). As observed in the HYP location, there was a positive response to N fertilization in NT and also the probability of exceeding a given yield was always greater for NT (Fig. 6). At LYP location, simulated water use by the crop was low with predicted values ranging between 100 and 300 mm. The low water use predicted by the model resulted in low crop yields with a null probability of obtaining more than 1.75 t ha^{-1} (Fig. 6). At this location, the two tillage treatments did not differ significantly on water use (Fig. 4). Simulated average yield was 18% higher under NT than under CT, and there was no response to N fertilization under either tillage system (Fig. 5). The expected yield with 50% probability was about 0.6 t ha^{-1} in CT and 0.75 t ha^{-1} in NT (Fig. 6). The unfertilized condition showed the highest probability of obtaining a given yield because of the strong drought conditions at this location.

Simulated crop water-use efficiency followed the same pattern since high crop yields were related to high WUE (Fig. 7). Simulated WUE ranged between 6 and 9 kg ha^{-1} mm^{-1} at HYP, 4 and 12 kg ha^{-1} mm^{-1} at MYP and 3 and 3.5 kg ha^{-1} mm^{-1} at LYP. Greater WUE was simulated in NT because of the lower evaporation/transpiration ratio. At HYP and MYP locations, simulated WUE was higher in NT and when N fertilization was applied at medium and high levels according to yield potential. At LYP location, the model predicted minor WUE differences between tillage systems and without response to N fertilization (Fig. 7).

Simulated NUE was high in HYP and MYP (80% and 70% respectively) and much lower in LYP (ranging between 23% and 37% for CT and NT, respectively). The increase of N rate diminished the simulated NUE by an 8%, 10% and 15% in HYP, MYP and LYP, respectively. Simulated nitrate leaching was low in the MYP and HYP sites, with values ranging between 1 and 10 kg NO_3^--N ha^{-1} yr^{-1} without significant differences between tillage systems. In LYP, simulated nitrate losses were higher, being 21 and 51 kg NO_3^--N ha^{-1} yr^{-1} for the medium and high N rate, respectively, without differences between tillage systems. Simulated N mineralization attained 47, 48 and 61 kg N ha^{-1} yr^{-1} in LYP, MYP and HYP, respectively, showing differences between tillage systems only in MYP with 47 and 57 kg N ha^{-1} yr^{-1} under CT and NT, respectively.

Figure 8 compares crop yield cumulative probability calculated from the 18-year observed data with the 50-yr crop yield cumulative probability predicted by the model for the MYP site. Simulated values showed great similarities with observed ones. Both suggest a greater probability of getting higher yields under NT than CT and greater crop yield response to medium rates of N fertilizer (i.e. 60 kg N ha^{-1}) compared to the control without nitrogen.

4. Discussion

4.1 Model performance as a tool for agricultural practices decision

The model simulated grain yield and WUE with a deviation lower than 15%. The two exceptions were observed during the last simulated year (i.e., 1999) when drought conditions were overestimated at HYP in CT and when crop stress due to pest attack at LYP in NT was not predicted by the model (Fig. 3). Furthermore, at MYP, fungi affected the experiment during the first year, which could explain the slight differences between observed and simulated values. These differences were not recorded in CT, which was less affected by fungi. However, fungi attacks leading to economic losses are rare under rainfed winter cereal production in the Ebro valley given the dry conditions during most of the crop development period and the low profitability. At MYP, the model simulated yield better than at HYP in the last year (dry year). At LYP, yield was optimally simulated in CT. In NT, treatments were greatly affected by pests, and average simulated yield was 30% higher than that observed.

At the HYP site, the simulated average yield for the first two years was 3342 kg ha^{-1} (average of all treatments), slightly lower than the obtained 3500 kg ha^{-1} (Fig. 3). Similar limitations due to the climatic variability of these Mediterranean conditions for simulating yield, WUE and nitrogen use efficiency (NUE) have been reported by Pala et al. (1996) using the CropSyst model and by Asseng et al. (2001) using the APSIM model. This is congruent with the results obtained in other works for the same conditions for yield and WUE (Harris 1995; Cantero-Martínez et al. 2007; Pala et al. 2007).

In the years in which soil water recharge was not a limiting factor, the model simulated well soil water content. However, in dry years (i.e., 1999), soil water content was not well simulated mainly because CropSyst overestimated soil evaporation. The model considers that the small amount of water that arrives to the soil surface is not able to infiltrate to deeper layers and consequently is more susceptible to be lost by evaporation. Other cause for such disagreement between observed and simulated data could probably be related to the very high evaporation of the surface layer resulting from the low amount of crop residues and to the incidence of pests that reduced the amount of crop biomass during the growing season particularly in NT.

Comparison of yield cumulative probability curves between the 50-years simulation and 18-years observed data in MYP suggests a very good model performance (Fig. 8). However, despite this good agreement, the 18-years crop yield observed data showed less response to medium and high N fertilization rates than the simulations carried out by the model. In similar studies which used CropSyst and other crop models to simulate crop growth in Mediterranean conditions, the same behaviour has been observed. In arid and semiarid conditions, Collins et al. (2008) and Ryan et al. (2009) suggested that biological and other not well understood processes that affect soil organic matter and N mineralization cycle may determine available N for the crop and, finally, crop yield.

4.2 Soil management approach for these conditions

The agreement between simulated and observed data was better for NT than for CT. The difference between tillage systems was more apparent when analysing the effect of drought on biomass accumulation. The CropSyst model simulated better drought effects on biomass in NT than in CT. During the driest year (i.e., 1999), crop yield and biomass were fairly well simulated for the NT unfertilized treatment but the model underestimated the NT high N rate treatment. In both cases, soil water content was well simulated. Therefore, there is the possibility that the model did not simulate well the response to N applications. This fact would explain the lack of adjustment in the NT high N rate treatment. This lack of response could be explained by some water uptake by the crop from below 100 cm depth, which was introduced as a threshold depth for water uptake in the model. Another reason could be that air temperature and rainfall were the only data used to calculate potential evapotranspiration. Stöckle et al. (1997) found an underestimation of sorghum yield using the Priestley-Taylor (P-T) submodel instead of the Penman-Montheith (P-M) submodel. This was probably because the P-T submodel calculates vapour pressure deficit (WPD) from temperature and the P-M model from air moisture, and WPD is directly correlated with crop biomass and yield in water-limited situations. During the year 1999, the overestimation of the soil evaporation from topsoil layers promoted an overestimation in the evapotranspiration that affected crop biomass and yield in the CT treatments. Consequently, the model simulated low water use by the crop, resulting in crop failure. However, the observed soil water content was higher than the modelled and, thus, observed grain yields greater than the predicted (Fig. 3). Wythers et al. (1999) suggested that the real process of soil evaporation is more complex than the one used by models, and that soil texture and the lapse of time since the last wetting could play an important role in the quantification of the amount and intensity of soil evaporation.

Yield potential in Mediterranean areas is limited by water availability to the crop. Conservation tillage systems as NT are capable to maintain and improve crop yields (Hernanz and Sánchez-Girón 1988; López-Bellido et al. 1996; López and Arrúe 1997; Mrabet 2000; Pala et al. 2000; Lampurlanés et al. 2001; Cantero-Martínez et al. 2003; Cantero-Martínez and Gabiña 2004; Cantero-Martínez et al 2007; López-Garrido et al 2014). Most of the works referenced above were carried out in short- or mid-term field experiments in the Mediterranean basin. Only in the LYP site, results did not show a clear advantage of NT compared to CT because of the already mentioned pest occurrence (Cantero-Martínez et al. 2003; Angás et al. 2006; Cantero-Martínez et al. 2007). Also, in Mediterranean areas with low yield potential, low crop yields and thus limited amount of crop residues result in a key limitation to the proper functioning of the conservation tillage systems due to the lack of a proper soil cover (Radford et al. 1992; Thomas et al. 2007).

The cumulative probability curves that we obtained from 50 years of simulation and 18 years of observed data showed the better performance of NT compared to CT in the long-term. The similarities between long-term observed and simulated data point out the usefulness of CropSyst as a decision tool for establishing NT as a best soil management practice under Mediterranean conditions.

4.3 N fertilization effect

Simulated NUE was higher when increasing the yield potential of the site, being the amount of soil water a major lever of these lasts. As previously reported by Angás et al. (2006) in the same sites, NUE decreased as the amount of fertilizer N increased. Simulated nitrate losses as leaching were very low in MYP and HYP as a result of the dry conditions of the rainfed semiarid systems of the Mediterranean with fine-textured soils where N leaching occurs after high intensity rainfalls and/or under shallow and stony soils, such as is the case of LYP (e.g. Ryan et al. 2009), leading to the loss of nitrate accumulated in the soil from previous seasons. Nitrogen mineralization values simulated by CropSyst were not affected by tillage system in LYP and HYP and were slightly higher under NT than CT in MYP. These differences observed between sites could be a consequence of the amount of crop residues returned to the soil and their management. Thus, while in LYP and MYP straw was spread on the soil, in HYP straw was removed to ease the establishment of the succeeding crop, fact that would led to similar C inputs between tillage systems in this site. In LYP, the lack of differences of biomass production and carbon inputs to the soil between CT and NT would reduce the possibility of an increase in soil organic matter when using NT. Regarding the differences simulated by the model between NT and CT in MYP, some authors reported a higher N mineralization when NT is maintained in the long-term when crop residues are returned to the soil surface as a result of greater substrate available for decomposition (e.g. Franzluebbers et al. 1995; Wienhold and Halvorson, 1999). Moreover, in semiarid Mediterranean systems, the greater protection of soil organic matter within aggregates under NT (Álvaro-Fuentes et al. 2009) could be counterbalanced by the higher amount of soil water stored under NT, which would enhance microbial activity and soil organic matter decomposition (Skopp et al. 1990; Lampurlanés et al. 2016). However, according to the simulations the amount of N mineralized in CT and NT in MYP only differed by 10 kg N ha^{-1} yr^{-1}. This low magnitude would not influence significantly the N fertilization strategy to use under the conditions of the experiment.

Unlike tillage system, differences among N fertilization rates were more dependent on the climate conditions of the year. In very dry years, with less potential for crop production, the probability of obtaining better yield is slightly greater for 0 N. However, in years with more available water the probability of achieving 3 t ha^{-1} is only 4% with no fertilization but 24% if N fertilization is applied. In water limited areas, it is quite frequent to observe that all available water is consumed by the crop no matter the N fertilization rate. However, the simulation runs showed an impact of N fertilization on crop biomass, yield and WUE. Using the 50% probability as a selection criterion (Fig. 6), it is possible to establish the optimum N fertilization strategy. With no N fertilization, the probability of yields higher than 1000 kg ha^{-1} is low. In fact, after 10-20 years, the model simulated a substantial depletion of soil nitrogen and an intense response of crop yield to N fertilizer. In very arid conditions (i.e., LYP), the model did not simulate a positive response to N fertilization. However, as the degree of aridity decreased (i.e. MYP and HYP conditions) the response to N increased but only to moderate levels of N applied (i.e. from no application to medium doses). The WUE was also affected by the N fertilization, increasing in a similar manner. In Mediterranean conditions, Pala et al. (2007) reported this same finding.

The interaction of tillage systems and N fertilization and the agronomic recommendations that can be established are two main outcomes from this study. The predicted response of crop yield and WUE to N fertilization was stronger under NT than under CT (Figs. 5 and 7), because more soil water and possibly less soil nitrogen was available (Cantero-Martínez et al. 2003). According to this observation, in the Mediterranean region, it is recommendable the use of NT as soil management system with moderate applications of N fertilizers.

5. Conclusions

The CropSyst simulation model simulated reasonably well the evolution of soil water content during the typical recharge periods of the Mediterranean cereal-based cropping systems. However, the model overestimated soil evaporation when rainfall was very low. The model predicted properly crop biomass and yield when the availability of water and nitrogen was not extremely limiting. Thus, the large underestimation of crop yield under drought conditions was associated with the overestimation of evaporation. Moreover, the model was not designed to predict the incidence of pests and diseases and for this reason it was not able to simulate yield reductions under these circumstances.

The application of the model to generate long-term series of output variables such as crop yield, allows establishing the best strategy for tillage and N fertilization. This study, in which three locations representing a wide range of aridity conditions typical of the Mediterranean areas were used, confirmed that NT is the best alternative to improve crop yield and water use efficiency. The 50 years of continuous simulation validated by the 18-year observed data supports this conclusion. In addition, the rate of N fertilization can be reduced about 50% of the current rates due to the lack of enough available water in the soil and depending on the degree of aridity no application is needed. According to the simulated and the observed long-term data, a higher rate of N fertilization can only be applied to NT systems in which greater soil water is available to the crop. Unlike, under intensive tillage no effect of N fertilization was observed and, thus, significant reductions of N rates are possible.

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Figure captions

Fig. 1 Simulated (lines) and observed (symbols) total crop biomass at HYP, MYP and LYP, high, medium and low yield potential sites, respectively, during three years (1996-1999) for the tillage (NT, no tillage and CT, conventional tillage) and N fertilization rate treatments (0 and 100, 120 and 150 kg ha^{-1}, for the HYP, MYP and LYP sites, respectively). Please, note the different Y-axis scale between sites.

Fig. 2 Simulated (lines) and observed (symbols) soil water content at the HYP and LYP (high and low yield potential, respectively) sites during three years (1996-1999) for the tillage treatments (NT; no-tillage and CT, conventional tillage) with no N applied.

Fig. 3 Simulated (■) and observed (□) grain yields at the HYP, MYP and LYP (high, medium and low yield potential, respectively) sites during three years (1996-1999) for the tillage (NT, no tillage and CT, conventional tillage) and N fertilization rate (no N and high N) treatments. Vertical bars indicate the standard error.

Fig. 4 Linear relationships between crop grain yield and water use for 50 simulated years at three fertilization rates under conventional (CT) and no-tillage (NT) at the HYP, MYP and LYP (high, medium and low yield potential, respectively) sites. Solid and dashed linear relationship lines correspond to CT and NT, respectively. *** indicates $P \leq 0.001$.

Fig. 5 Simulated barley grain yields for 50 years as a function of tillage and N fertilization at the HYP, MYP and LYP (high, medium and low yield potential, respectively) sites. Please, note the different Y-axes between sites. Vertical bars indicate the standard error.

Fig. 6 Probability of crop yields after 50-year simulation for the three N fertilization rates and two tillage systems at the HYP, MYP and LYP (high, medium and low yield potential, respectively) sites. Please, note the different X-axes between sites.

Fig. 7 Water-use efficiency (kg ha^{-1} mm) for 50-year simulation as a function of tillage and N fertilization rate the HYP, MYP and LYP (high, medium and low yield potential, respectively) sites. Vertical bars indicate the standard error. Please, note the different Y-axes between sites.

Fig. 8 Probability of crop yields after 18-year of observed data and 50-year simulation for three N fertilization rates (0, 60 and 120 kg N ha^{-1}) and two tillage systems (CT, conventional tillage; NT, no-tillage) in the MYP (medium yield potential) site.

Table 1. Site and soil characteristics for the 0-25 cm soil layer in the three experimental sites (HYP, MYP, LYP: high, medium and low yield potential, respectively).

Site and soil characteristics	Guissona (HYP)	Agramunt (MYP)	Candasnos (LYP)
Annual precipitation (mm)	475	430	352
Annual ETo (mm)	800	855	1224
Annual water deficit (mm) [a]	325	425	872
Soil classification [b]	Fluventic Mesic Xerocrept	Typic Xerofluvent	Typic Haplocalcid
Effective depth	100	100	50
Soil organic matter concentration (%)	2.52	0.90	2.00
Stoniness (% vol.)	0	0	30
Texture	Silty loam	Loam	Silty loam
Particle size distribution			
Sand (%)	27.0	46.4	23.2
Silt (%)	53.0	41.8	54.2
Clay (%)	20.0	11.8	22.6
Bulk density (Mg m^{-3})	1.39	1.45	1.20
Soil water content at permanent wilting point (m^3 m^{-3})	0.150	0.050	0.125
Soil water content at field capacity (m^3 m^{-3})	0.316	0.310	0.270

[a] Calculated as the difference between mean annual precipitation and mean annual ETo.

[b] According to the USDA classification (Soil Survey Staff, 1994).

Table 2. Crop parameters required by CropSyst of the barley cultivars Barbarrosa (used at Guissona, HYP), Hispanic (used at Agramunt, MYP) and Albacete (used at Candasnos, LYP). HYP, MYP and LYP stand for high, medium and low yield potential, respectively.

Parameter	Barbarrosa	Hispanic	Albacete
Measured or estimated from field data			
Harvest index	0.43	0.42	0.39
Maximum expected LAI	4.5	7.0	3.0
Fraction of max. LAI at physiological maturity	0.2	0.2	0.2
Specific leaf area (m^2 kg^{-1})	25.7	27.9	16.6
Maximum N concentration during early growth (%)	3.50	4.40	3.50
Maximum N concentration at maturity (%)	1.20	1.30	1.40
Minimum N concentration at maturity (%)	0.80	0.90	0.90
Maximum N content of standing stubble (%)	0.40	0.75	0.70
Area to mass ratio of residue cover (m^2 kg^{-1})	3.50	3.50	3.00
Maximum rooting depth (m)	1.20	1.20	1.20
ET crop coefficient at full canopy	1.15	1.15	1.15
CropSyst manual and other references			
Light to above ground biomass conversion (g MJ^{-1})	2.56	2.56	2.56
Actual to potential transpiration ratio that limits leaf area growth	0.20	0.20	0.20
Actual to potential transpiration ratio that limits root growth	0.20	0.20	0.20
Optimum mean daily temperature for growth (ºC)	15	15	10
Maximum water uptake (mm)	8.5	8.5	8.5
Leaf water potential at the onset of stomata closure (J Kg^{-1})	-2000	-2000	-2000
Wilting leaf water potential (J Kg^{-1})	-3000	-3000	-3000
Stem/leaf partition coefficient	3.0	3.0	3.0
Leaf duration (degree-days)	800	800	800
Leaf duration sensitivity to water stress	1.50	1.50	1.50
Extinction coefficient for solar radiation	0.50	0.50	0.50
Sensitivity to water stress:			
During flowering	0.05	0.05	0.10
During grain filling	0.05	0.05	0.30
Translocation to grain factor	0.30	0.30	0.30
Decomposition time constant for residues	60	60	60
Nitrogen uptake adjustment	1.0	1.0	1.0
Calibrated			
Above ground biomass transpiration coefficient (KPa kg m^{-3})	4.90	5.60	4.20
Degree days at emergence	120	120	120
Degree days to maximum LAI	1140	1050	1100
Degree days to begin flowering	1300	1200	1300
Degree days to begin grain filling	1400	1350	1400
Degree days to begin physiological maturity	1870	1770	1810
Amount of residual nitrogen per soil layer (kg ha^{-1})	4.0	5.0	2.0

Table 3. Statistical criteria showing the performance of the CropSyst model when simulating different soil and crop variables. Data corresponds to the conventional- and no-tillage treatments without N fertilization and with high N fertilization rates in the Guissona, Agramunt and Candasnos experimental fields i.e., HYP, MYP and LYP, high, medium and low yield potential, respectively).

Statistical criteria	Soil water content (m^3 m^{-3})	Aerial biomass (kg DM ha^{-1})	Grain yield (kg DM ha^{-1})
n	144	144	36
EF	0.71	0.75	0.46
MD	0.005	274.8	39.6
rRMSE (%)	24	41	43

Figure 1

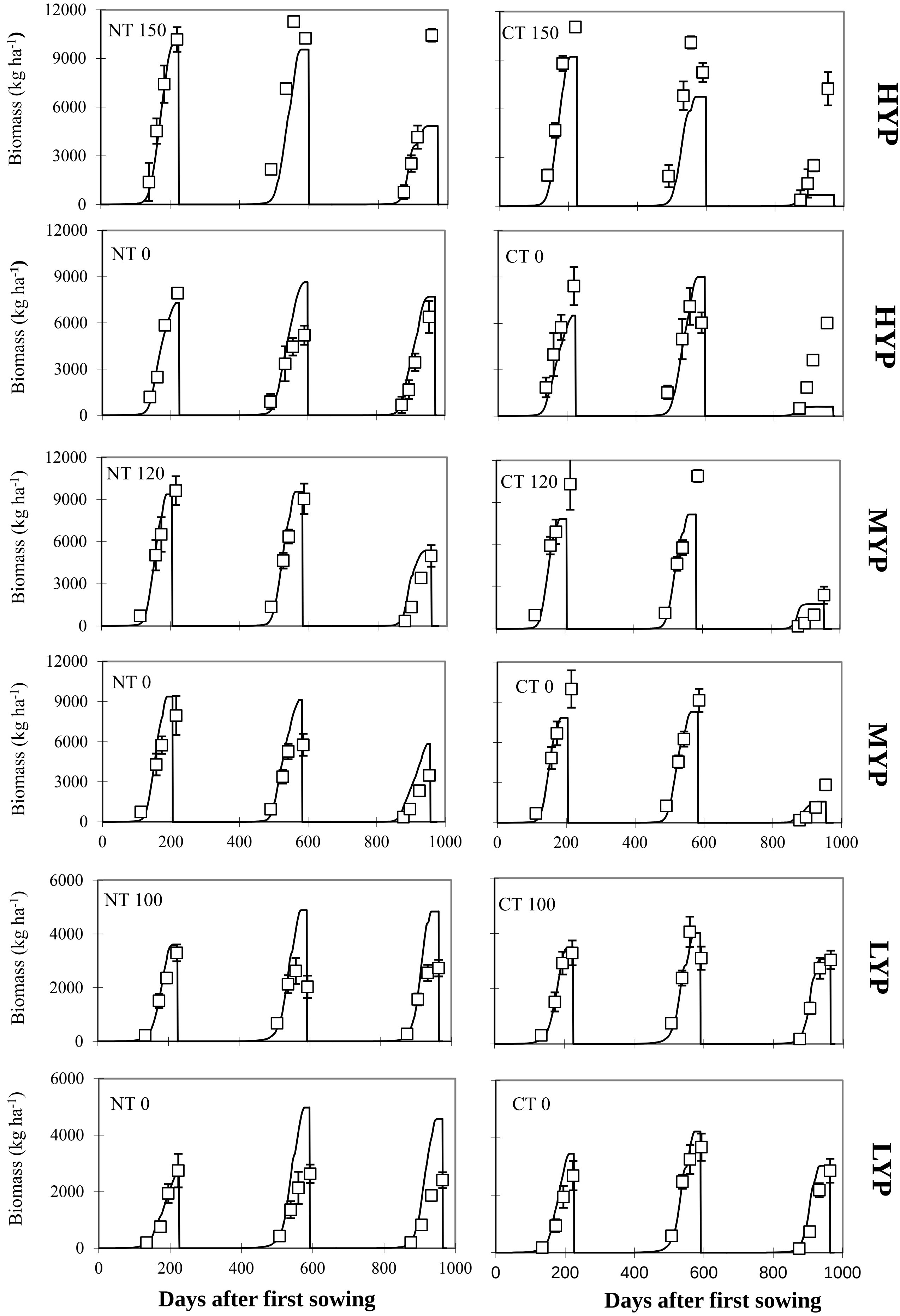

NT 150
CT 150
HYP
NT 0
CT 0
HYP
NT 120
CT 120
MYP
NT 0
CT 0
MYP
NT 100
CT 100
LYP
NT 0
CT 0
LYP
Biomass (kg ha-1)
0
3000
6000
9000
12000
2000
4000
200
400
600
800
1000
Days after first sowing

Figure 2

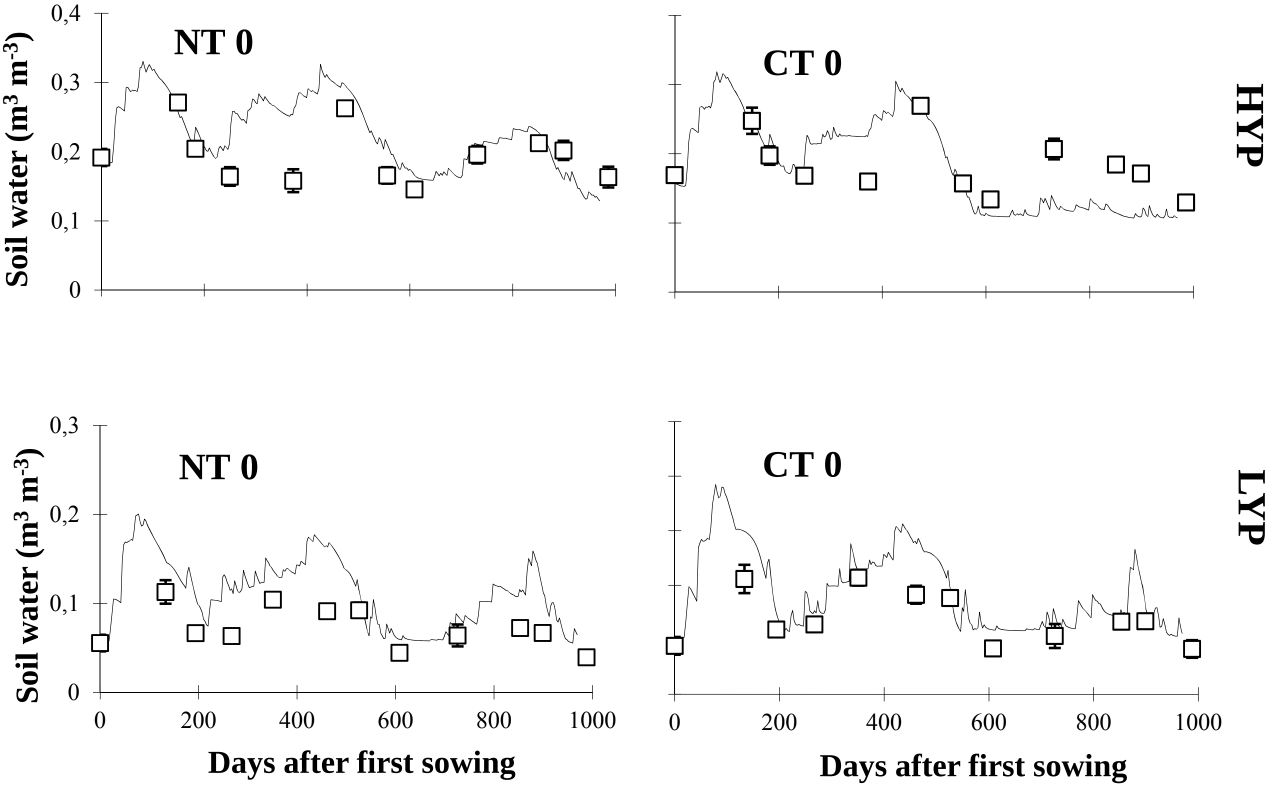

Soil water (m3 m-3)
NT 0
CT 0
HYP
LYP
0,4
0,3
0,2
0,1
0
0
200
400
600
800
1000
Days after first sowing

Figure 3

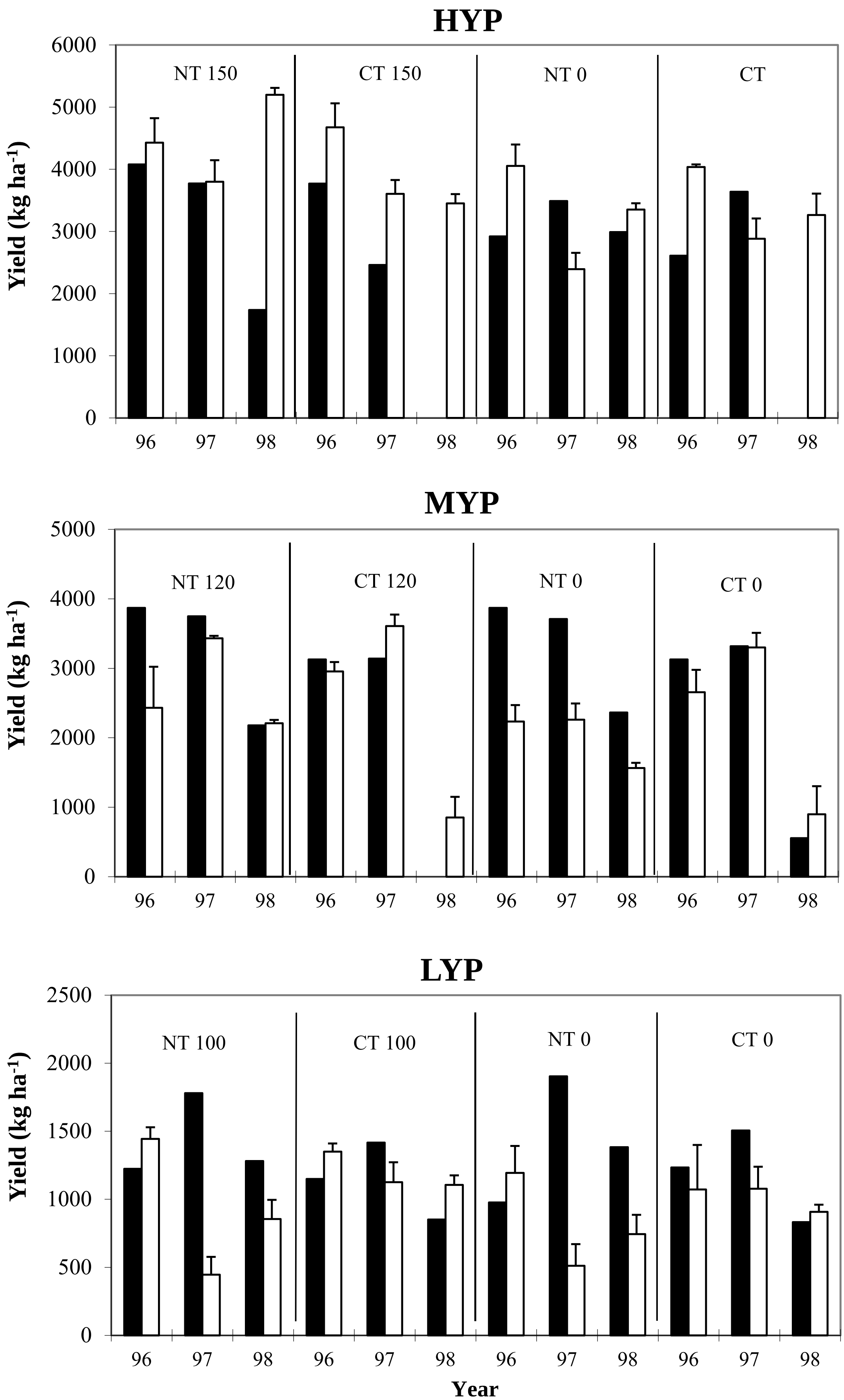
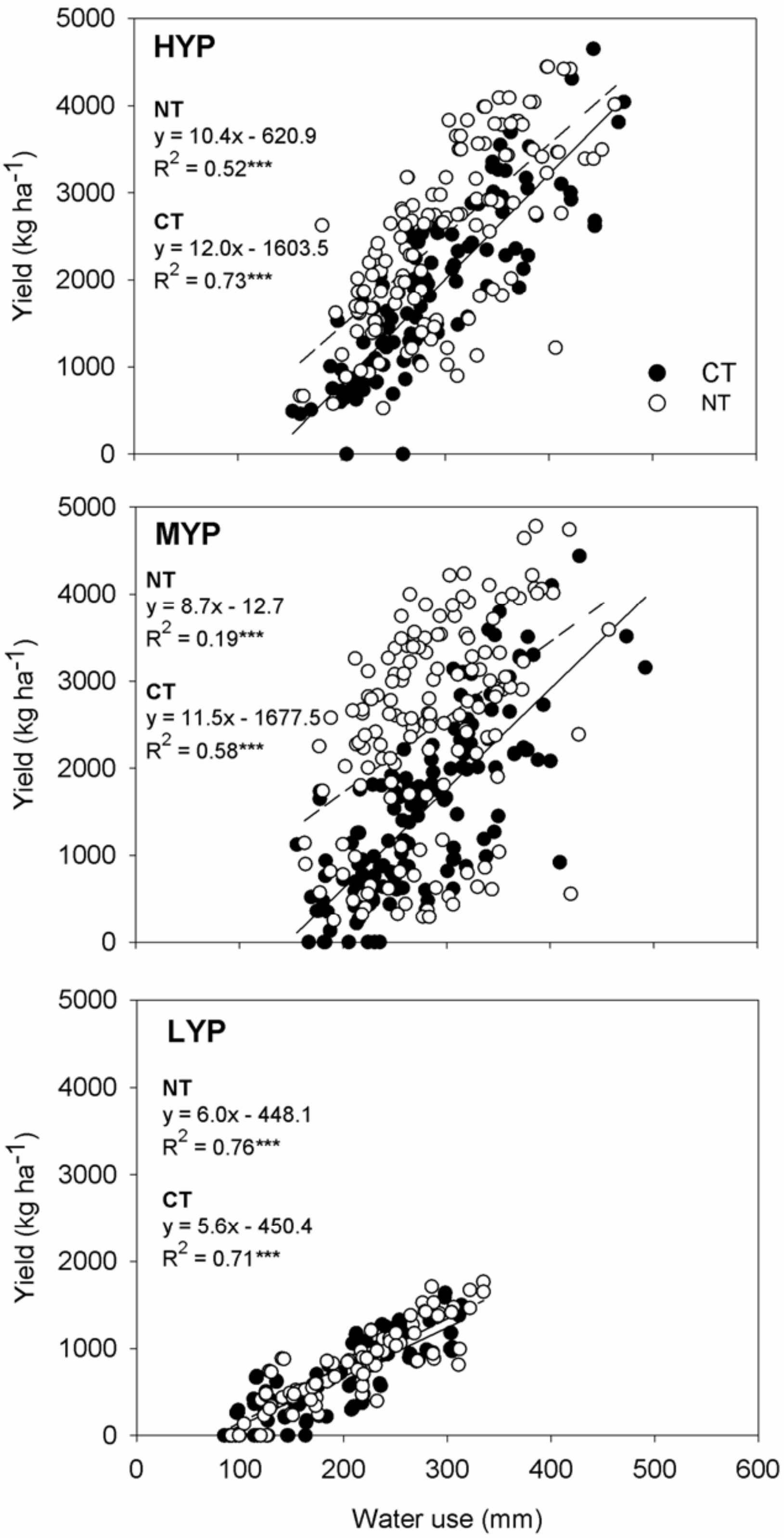

HYP
Yield (kg ha-1)
NT 150
CT 150
NT 0
CT
MYP
NT 120
CT 120
NT 0
CT 0
LYP
NT 100
CT 100
NT 0
CT 0
Year

Figure 4



HYP
NT
y = 10.4x - 620.9
R2 = 0.52***
CT
y = 12.0x - 1603.5
R2 = 0.73***
CT
NT
MYP
NT
y = 8.7x - 12.7
R2 = 0.19***
CT
y = 11.5x - 1677.5
R2 = 0.58***
LYP
NT
y = 6.0x - 448.1
R2 = 0.76***
CT
y = 5.6x - 450.4
R2 = 0.71***
Yield (kg ha-1)
Water use (mm)
0
1000
2000
3000
4000
5000
0
100
200
300
400
500
600

Figure 5

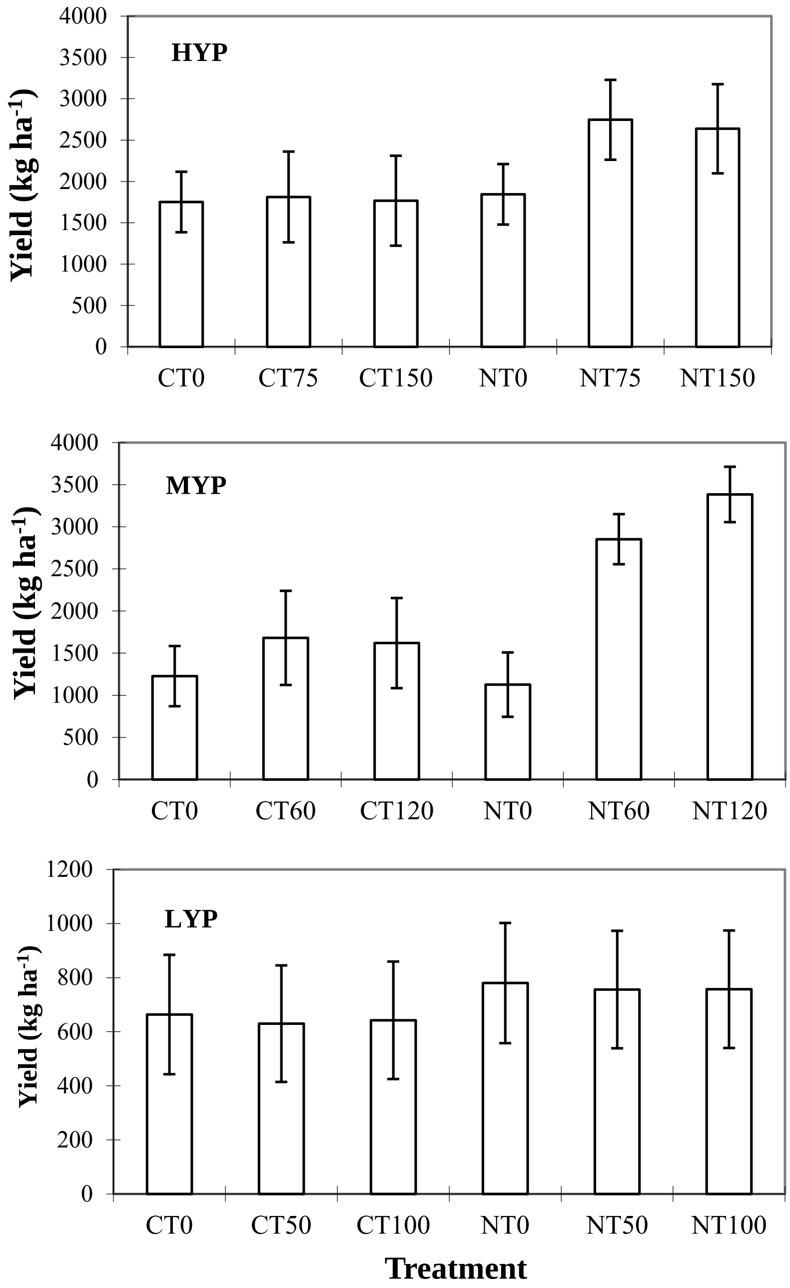

HYP
Yield (kg ha-1)
4000
3500
3000
2500
2000
1500
1000
500
0
CT0
CT75
CT150
NT0
NT75
NT150
MYP
Yield (kg ha-1)
4000
3500
3000
2500
2000
1500
1000
500
0
CT0
CT60
CT120
NT0
NT60
NT120
LYP
Yield (kg ha-1)
1200
1000
800
600
400
200
0
CT0
CT50
CT100
NT0
NT50
NT100
Treatment

Figure 6

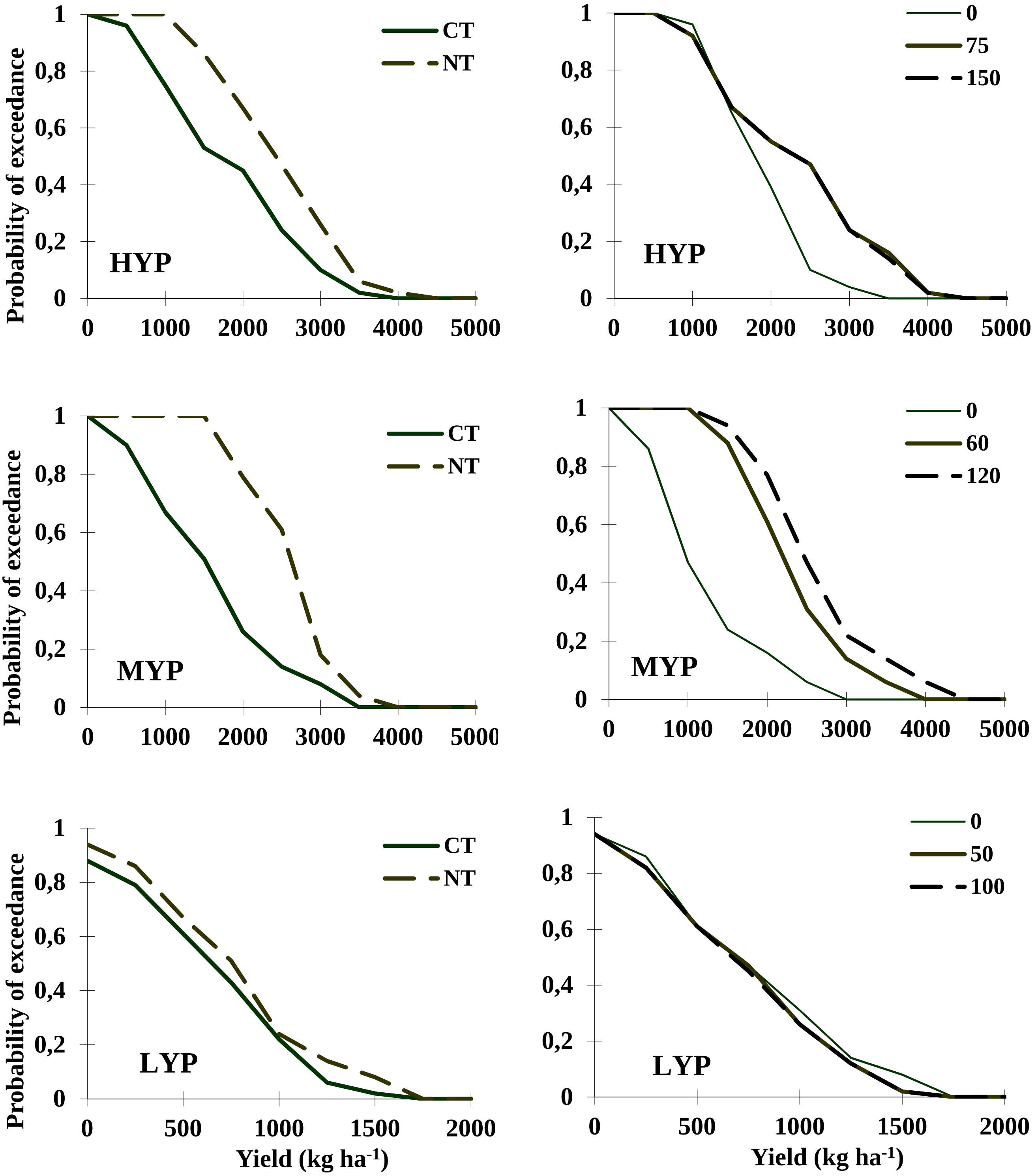

Probability of exceedance
1
0,8
0,6
0,4
0,2
0
0
1000
2000
3000
4000
5000
500
1500
CT
NT
0
75
150
60
120
50
100
HYP
MYP
LYP
Yield (kg ha-1)

Figure 7

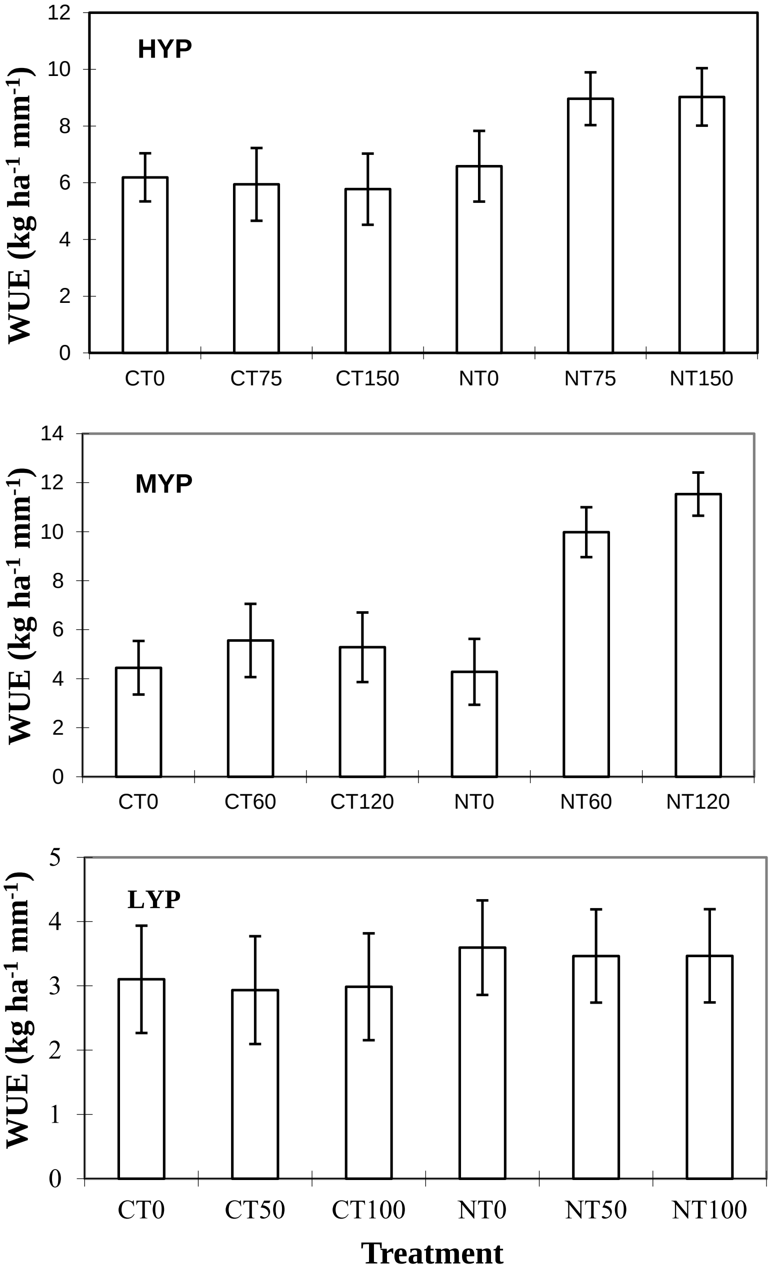
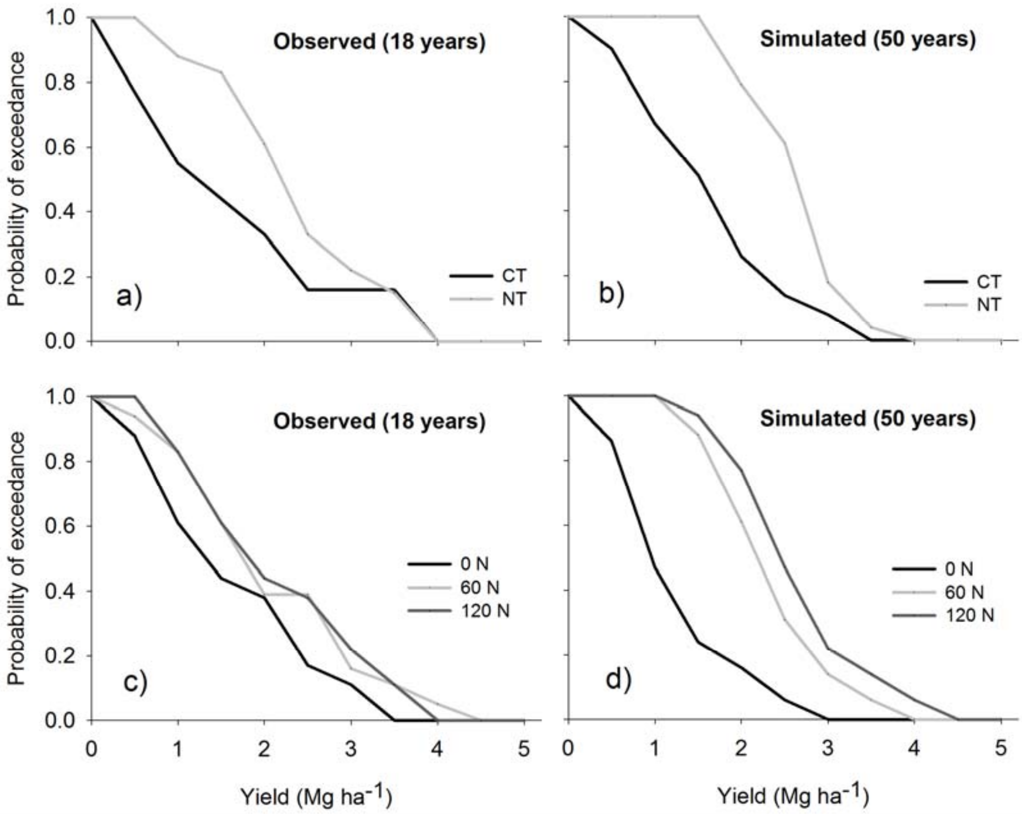

HYP
WUE (kg ha-1 mm-1)
0
2
4
6
8
10
12
CT0
CT75
CT150
NT0
NT75
NT150
MYP
WUE (kg ha-1 mm-1)
0
2
4
6
8
10
12
14
CT0
CT60
CT120
NT0
NT60
NT120
LYP
WUE (kg ha-1 mm-1)
0
1
2
3
4
5
CT0
CT50
CT100
NT0
NT50
NT100
Treatment

Figure 8


Observed (18 years)
Simulated (50 years)
Probability of exceedance
CT
NT
a)
b)
Observed (18 years)
Simulated (50 years)
0 N
60 N
120 N
c)
d)
Yield (Mg ha-1)
Yield (Mg ha-1)
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5