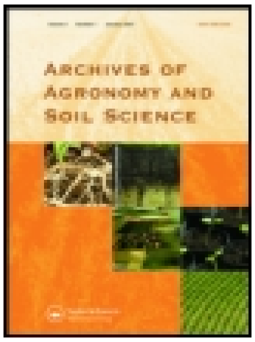

Archives of Agronomy and Soil Science

ISSN: 0365-0340 (Print) 1476-3567 (Online) Journal homepage: http://www.tandfonline.com/loi/gags20

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To cite this article: Ruzica Stricevic, Aleksandar Simic, Alpaslan Kusvuran & Marija Cosic (2016): Assessment of AquaCrop Model in the Simulation of Seed Yield and Biomass of Italian Ryegrass, Archives of Agronomy and Soil Science, DOI: 10.1080/03650340.2016.1275580

To link to this article: http://dx.doi.org/10.1080/03650340.2016.1275580

Accepted author version posted online: 21 Dec 2016.

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Download by: [Gazi Universitesi] **Date:** 22 December 2016, At: 12:34

Publisher: Taylor & Francis

Journal: *Archives of Agronomy and Soil Science*

DOI: 10.1080/03650340.2016.1275580

Assessment of AquaCrop Model in the Simulation of Seed Yield and Biomass of Italian Ryegrass

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Abstract

Given that the optimal sowing rate and inter-row spacing of Italian ryegrass raised for seed have not been determined, the objective of this research was to assess the effect of crop density on biomass and seed yields under different climate conditions, applying the AquaCrop model. The data came from experiments conducted under moderate continental climate conditions at Stitar (Serbia) and Mediterranean climate conditions at Cukurova (Turkey). At Stitar, there were three different inter-row spacings (high (S_d), medium (S_m), and low (S_w) crop densities), while at Cukurova there was only high crop density (S_n). In the calibration process, the initial canopy cover, canopy expansion and maximal canopy cover were adapted to each crop density, while the other conservative parameters were adjusted to correspond to all climate conditions. Calibration results showed a very good match between measured and simulated seed yields; the values of the coefficient of determination (0.922). The biomass simulation was very good for Cukurova (R^2=0.97), but somewhat poorer for Stitar (R^2=0.72). Other statistical indicators were high such as Willmott index of agreement of both the calibrated and validated data sets, for both study areas >0.916 and normalized root mean square error (NRMSE) in the range from 9%–18%. The AquaCrop model was found to be more reliable for Italian ryegrass biomass and seed yield predictions under mild winter climate conditions, with adequate water supply, compared to moderate climate and water shortage conditions.

Keywords*:* AquaCrop, crop density, *Lolium multiflorum*, modeling, water stress

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Introduction

Italian ryegrass (*Lolium multiflorum* Lam. syn. *L. italicum* A.Br.), is the most extensively grown grass in moderate climates along with the English ryegrass (*Lolium perenne* L.). Seed production highly depends on sowing rate and inter-row spacing, as well as climate condition, soil fertility, water availability, and therefore it is still in focus of many research efforts (Kusvuran and Tansi 2011; Simic et al. 2009). The application of models certainly facilitates the determination of impact of mentioned factors on biomass and seed yield of Italian ryegrass.

Numerous and essentially different models have been developed to simulate grass yields. A decision tree model was used to assess the luxuriance of the three major herbage plants (ryegrass, browntop and white clover) in New Zealand, based on various criteria that sort data according to the nature of the studied variable (e.g. slope, soil, fertility, precipitation totals, temperatures, etc.) (Wan et al. 2009). McCall and Bishop-Hurley (2003) developed a model that simulates the biomass of herbage grasslands in a moderate climate. The model is energy driven and specific in that it takes into account radiation energy interception, the parts of the plant not engaged in photosynthesis, radiation energy use efficiency, the time of development of reproductive organs and the relative ratio of energy utilization in vegetative and generative stages. The model was improved by Romera et al. (2009) replacing an empirical senescence function with the new function based on leaf lifespan, measured in thermal time, which is characteristic of a given grass species, and can be measured independently or sourced from the literature. Based on a calculation model proposed by Thornley and Johnson (1990), Lazzarotto et al. (2009) developed the dynamic plot-scale PROGRASS model for simulating the growth and yield of a mixture of mowed grass and clover. They devoted special attention to the development and interaction of grass and clover root systems and the root and shoot growth ratio. Vaze et al. (2009) used the carbon-driven generic CLASS PGM model to simulate yields of perennial and annual mixtures of grasses. Duru et al. (2009) adapted a mono-specific grass model to enable yield simulation of grasslands featuring several similar plant species. The model is based on the transformation of solar radiation to biomass and was developed further by grouping plant species and addressing different management practices. The extent of biophysical processes, governed by climate parameters and nutrient availability, was adjusted in the model to each phenophase of growth, specific to each plant species in the grassland. Riedo et al. (1998) developed a mechanistic model to simulate the growth process, annual production of grassland biomass and nitrogen budget. They emphasized the importance of differentiating the developmental and reproductive stages of growth. The difference between measured and simulated dry mass was from 6 to 21%, depending on location, year and grass-cutting regime. The largest variations were noted in years that featured extreme drought, cold or water-logging. Creighton et al. (2012) also simulated grass development under different growing conditions (pasture, cutting, various densities). Kroes and Supit (2011) used the WOFOST and SWAP models to study grass growth under present conditions and as impacted by climate change, as well as in favorable and stress conditions (salinity, water-logging, drought). Although short-lived grasses, including Italian ryegrass, occupy considerable land areas worldwide, not many papers report studies of plant growth from the perspective of yield and biomass prediction, to facilitate planning and make it more reliable in terms of irrigation needs and selection of

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sowing rate and stand density for given soil and climate conditions. Abraha and Savage (2008) used the CropSyst model to simulate the water budget and determine the irrigation water demand of Italian ryegrass. Fessehazion et al. (2014) also used a soil water balance (SWBSci) model to study irrigation, nutrient and salt management strategies. The model was calibrated and validated on Italian ryegrass for different irrigation and nitrogen-based fertilizer application regimes, and then the yields and water and nitrogen losses were assessed.

As such, past research focused on the yields of perennial and short-lived grasses, and the effect of nitrogen or water availability on yields. The effect of sowing rate of uncut short-lived grasses on biomass and seed yields under different climate conditions has not been tested to date by any model. The objectives of this research is to parametrize AquaCrop model for simulation biomass and seed yield of Italian ryegrass grown in two different climatic condition and soil type. Biomass and yield are obtained from four different sowing rates, forming different stand density. The second aim was to examine whether model could be used in planning sowing rate and seed yield elswere. AquaCrop is water driven model, relatively user friendly and reliable for yield assessment and field management practice (Steduto et al. 2009; Raes et al. 2009). Aquacrop model was successfully used either for assessment of yield and biomass of main field crops such as maize (Hsiao et al. 2009), wheat (Mkhabela and Bullock 2012; Iqbal et al. 2014), sunflower (Todorovic et al. 2009) for prediction of planting date and irrigation management (Araya et al. 2010; Geerts et al. 2010) or wheat yield prediction when irrigated with saline water. Aquacrop model was also used to optimize deficit irrigation scheduling for cotton, potato and tomato (Linker et al. 2016). According to the research reported by Smit et al. (2008), there is a high correlation between grass productivity and annual precipitation totals. It is for this reason that the water-driven AquaCrop model, V 4.0 was selected.

Materials and Methods

Experimental Data

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The input data needed for the FAO AquaCrop model were collected at two test sites: Stitar, Serbia (44° 47' N latitude; 19° 35' E longitude, 79 m a.s.l.) and Cukurova, Turkey (37° 00' N, 35° 18' E, 161 m a.s.l.).

To characterize the climate of the study areas, meteorological data recorded over a period of 30 years (1981-2010) from the nearest meteorological stations (at Sremska Mitrovica for Stitar and Balcali for Cukurova) were used. The Stitar site features a moderate climate, with four distinct seasons. The mean annual precipitation total at Stitar was 614 mm (353 mm in the growing season). The mean annual temperature was 11.3°C. The mean annual air humidity was 76% and the wind speed at a height of 2 m 1.65 m s^{-1}. The coldest period was in January, with an average temperature of 0.1°C, and the warmest in July, 21.5°C (Hydro-meteorological services of Serbia 2014). The Cukurova site enjoys a Mediterranean climate. The summer season is warm and dry, and winters are temperate and rainy. Over 60 years (1954-2013), the average annual precipitation total is 656.1 mm. Average relative humidity is 66.4%. The average temperature is 19.1°C. January is the coldest month 9.6°C, and August the warmest, 28.5°C (Cukurova University 2007, Turkish state meteorological service 2014).

The soil in the Stitar study area can be characterized as gleysols of a heavy mechanical composition. The soil's chemical reaction was found to vary from (pH in H_2O) 6,19 to 8.8 in the deeper layers, due to the presence of $CaCO_3$. The humus-accumulating horizon was 0 – 30 cm deep, the texture was that of clay and the organic carbon content was 1.62% – 1.86%. The second horizon (30 – 50 cm) was made up of silty clay and the third of clay. All the soil horizons featured moderate levels of total organic nitrogen (0.1% – 0.2% N) determined by Kjeldhal method and potassium (K_2O 12.5 – 15 mg·kg^{-1}), and were poor in phosphorus (P_2O_5 1.2 – 3 mg·kg^{-1}), determined by AL method by Egnér-Riehm (Egnér et al. 1960). The soil structure was parallelepiped. Air porosity varied from 0.08 to 0.11 cm^3 cm^{-3}. The mean volumetric soil moisture across the soil section at field capacity and the wilting point were 0.44

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cm^3cm^{-3} and 0.26 cm^3cm^{-3}, respectively. The total available soil water (TAW) was calculated from the difference between field capacity and wilting point, which was 180 $mm{\cdot}m^{-1}$.

The soils at the Cukurova site were regosols, with almost flat and near-flat topographies. The soil depth was 80 cm on average. The texture of soil was clayey across the entire depth (silt 27 – 28%, sand 14 – 18%, clay 55 – 58%). The organic carbon content was 1.1 – 0.6%, and that of nitrogen 0.098 – 0.137%, phosphorus, P_2O_5 40.8 $kg{\cdot}ha^{-1}$, potassium K_2O 71.2 – 63.5% and $CaCO_3$ 24 – 27%. The soil was slightly alkaline (pH of soil water extract 7.47 – 7.60) (Cukurova University 2003).

At Stitar, the experiments were based on a randomized block design with nine treatments and four replications in three consecutive years (2003/2004 – 2005/2006). The size of each plot was 4m × 2.5 m. Each year in the autumn, before sowing of tetraploid Italian ryegrass of the Tetraflorum variety (*Lolium multiflorum cv. Tetraflorum*), the soil was fertilized with 20 $kg{\cdot}ha^{-1}$ of N, 90 $kg{\cdot}ha^{-1}$ of P_2O_5 and 70 $kg{\cdot}ha^{-1}$ of K_2O, and in the spring nitrogen was applied at different rates (0, 50 and 100 $kg{\cdot}ha^{-1}$ N). No statistically significant difference in biomass, row spacing and seed yield to fertiliser treatments was observed, so these treatments were not considered further. The research focused on different sowing rate and interrow stand densities:

- High crop density (S_d), obtained by 20 kg ha^{-1} of seed, inter-row spacing 20 cm, where maximal canopy cover was 85%,
- Medium crop density (S_m), obtained by 15 kg ha^{-1} of seed, inter-row spacing 40 cm, where canopy cover was 75%
- Low crop density (S_w), obtained by 5 kg ha^{-1} of seed inter-row spacing 60 cm, where maximal canopy is about 65%.

At Cukurova, two experiments were conducted with Italian ryegrass (*Lolium multiflorum, cv. Caramba*).

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The first experiment was of a randomized block design, with five treatments and three replications in two consecutive years (2002/2003-2003/2004). The row spacings were 15, 20, 25, 30 and 35 cm. Seed rate was 45kg ha^{-1} at all row spacings, and row spacing had no significant effect on seed yield and biomass, so data were averaged across row spacing treatments, and designated high crop density (S_d) in subsequent analyses. The size of each plot was 4.5 m × 8m = 36 m^2. All treatments were fertilized four times, with a total of 280 kg·ha^{-1} of N (split application) and 180 kg·ha^{-1} of P_2O_5.

The second experiment was conducted in 2003/2004-2004/2005, also with a randomized block design with eight treatments and three replications consisted of different N rates, and we used data from one well-fertilized. The size of each plot was 3.6 m × 8 m = 28.8 m^2. The sowing rate was 45 kg ha^{-1}, row spacing was 30 cm, denoted also by S_d in this paper.

The climate conditions are shown in Table 1. Irrigation was applied only at Cukurova, using a sprinkler irrigation system. To ensure sufficient amounts of readily available water for the growth of Italian ryegrass, irrigation was applied four times each year. The amounts of water are shown in Table 1.

[Table 1 near here]

The depth of the root system at Stitar was generally 0.6 m (depth was obtained from experiments carried out in transparent pots), while at Cukurova it was up to 0.8m, due to greater water use and drier conditions. The main difference between the two varieties of Italian ryegrass was the harvest index, which was 15%, on average, in the case of cv. Tetraflorum (with large deviations, min. 11.3 to max. 25.3%), and 8%, on average, in the case of cv. Caramba (with much smaller deviations, min. 6.4 to max. 8.7%).

Model Parameters and Input Data

The FAO AquaCrop model has been described in detail by Steduto et al. 2009 and Raes et al. 2009. This paper will mention only those parameters that are relevant to biomass and yield simulation of Italian ryegrass.

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The climate input data for the two study areas included: the daily value of reference evapotranspiration calculated by the FAO Penman-Monteith method (Allen et al. 1998), daily values of maximum and minimum air temperatures, and daily sums of precipitation during the study period. Irrigation depths and dates were input data for the Cukurova site only.

Italian ryegrass is a C3 grass that is dormant at low temperatures. At Stitar, the winters were cold and long, with sub-zero temperatures (occasionally as low as -24°C, with or without snow), so the dormancy period was longer. After the cold period, several days of above-zero temperatures were needed for tillering and rapid growth. Conversely, at Cukurova, there was intensive tillering during the winter months, due to the mild climate (average temperature above 10°C). It was noted in both study areas that growth decelerated at temperatures below 5°C, such that this temperature was taken as T_{base} in both cases. The upper temperature used was 30°C, the same as in Lazzarotto et al. (2009). In South Africa, T_{base} was 4°C and T_{up} 25°C (Abraha and Savage 2008). Due to the large difference in GDD between the two study areas, but also because of similar phenophases, and plant response to daylength, the "calendar day" option was selected.

Given that AquaCrop, Version 4.0, does not contain a default file for Italian ryegrass, the starting point of the calibration process included the entry of: crop density, C_3 crop option, and recorded crop growth stages. The crop density option was based on coverage during germination and the values were consistent with those used in other models (Abraha and Savage 2008). Initial canopy cover (CCo) as well as maximal canopy cover (CCx) differed among treatments, due to different seed rate (Table 3). The linear trend was obtained between CCo and seed yield (r^2=0,98) in comparison with seed rate and seed yield (r^2=0,99). There is also linear trend between seed rate and biomass production (r^2=0,99). The similar match was observed between CCo and biomass production with (r^2=0,87).

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Apart from experimental results, the sensitivity of the plant to temperature conditions, water stress and yielding was compared to the results reported in the literature (Riedo et al. 1998; Duru et al. 2009; Lazzarotto et al. 2009; Slewinski 2012).

The model was calibrated through an iterative process, using measured crop growth variables in both locations, such as root depth, observed phenological stages, canopy cover (obtained from photos that were analysed), harvest index, seed yield and biomass (Simic et al. 2009; Kusvuran 2011) parameters estimated from available data, and derived growing coefficients of dense inter-row spacing and highest sowing rate, as high plant density produces the highest yield and biomass. The crop was well-watered throughout the growing period, 2004/2005 at Stitar. Calibration for water stress was based on yield and biomass obtained for the growing seasons of 2003/2004 and 2005/2006 at Stitar.

The majority of the parameters were the same values throughout the study period in both study areas, such as conservative parameters: water productivity (WP), temperature and water stress, aeration stress, basal crop coefficient (Kcb), and crop development. Variations were related only to the crop cover, depending on inter-row spacing and the harvest index (HI) of the crop variety. The values of the parameters used in the AquaCrop model are shown in Table 2 for both locations.

[Table 2 near here]

The model was validated using data derived from the following scenarios: medium row spacing (S_m) treatment and wide row spacing – low crop density (S_w) at Stitar, and high crop density (S_d) at Cukurova.

Data Analysis

Five statistical methods were used to analyze and compare yield data derived from field experiments and simulations. The first was the root mean square error (*RMSE*) method and normalized *NRMSE*:

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$$RMSE = \left[\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \right] \quad [1]$$

where: S_i and M_i = simulated and measured values, respectively, and n = number of observations. The *RMSE* unit is the same for both variables (Mg·ha^{-1}), and the model's fit improves when *RMSE* tends toward zero, whereas the NRMSE unit is %.

$$NRMSE = \left[\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \right] * \frac{100}{\overline{M}} \quad [2]$$

Mean bias error (MBE), which refers only to an error that is systematic in nature.

$$MBE = \left[\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2 \right] \quad [3]$$

The index of agreement (d) was calculated using the Willmott (1982) equation:

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \bar{M}\right| + \left|M_i - \bar{M}\right|\right)^2} \quad [4]$$

where: $\bar{S}$ and $\bar{M}$ = average values of measured data. The index of agreement is a descriptor and its values range from 0 to 1. The model simulated the studied parameter better as the value approached 1.

The coefficient of determination R^2 is defined as the squared value of the Pearson correlation coefficient. It ranges from 0 to 1, with values close to 1 indicating a good agreement. This parameter, even with a high R^2, cannot indicate whether the model overestimates or underestimates the value.

$$R^2 = \frac{\sum\left(Mi - \overline{M}\right)\left(Si - \overline{S}\right)}{\sqrt{\sum\left(Mi - \overline{M}\right)^2 \sum\left(Si - \overline{S}\right)^2}} \quad [5]$$

Results

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The main characteristics of Italian ryegrass relevant to the parameterization of the AquaCrop model for both study areas are shown in Table 3. The average germination period at Stitar was 15 days and at Cukurova 13 days. Blooming began on day 206±6 after sowing at Stitar and day 201±10 at Cukurova. The total growing period to seed yielding was 257±9 at Stitar and 251±8 at Cukurova. The harvest dates were also similar and this is attributable to the ability of the plant to continue growing after cutting or exposure to stress, if conditions for development are favorable.

[Table 3 near here]

Despite very different climate conditions in the two study areas, it should be noted that the sowing periods were similar, as were the growing periods. It is apparently the response of ryegrass to daylenght and this characteristic facilitated the parameterization of the growth of Italian ryegrass under different climate and soil conditions. The simulation results for Italian ryegrass using the calibration data set are presented in Table 4. The calibration results show a good match between measured values and those simulated by the model, when plants were well-supplied with water. The variations in biomass and seed yields were 0.5 – 9%, deemed to be virtually insignificant. However, under drought conditions, which were present for a while before and partly during the germination period in 2003/2004, seed yields varied (27.1%), while biomass did not in comparison with simulated ones. Contrary to the first year of research, in 2005/2006 it was vice-versa: only biomass deviated (-21.3%), while seed yields were at -1.17%. The reason was inadequate water supply from germination to dormancy, as the plant entered the cold part of the year unprepared and needed a long time to recover. Yielding did occur, because there was sufficient water supply, but only in the first days of blooming. Because of stress, the plant used stored assimilates not to develop biomass, but for seeds. Unfortunately, the model could not simulate such subtle changes (it considers that there is dormancy at both -1 and -24°C, but the plant does not tolerate these temperatures equally, especially when there is no snow cover). It should be noted that a similar deviation from average values was also observed in the measured data (15%). In Cukurova site simulation

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results mached very well with measured ones, obtaining neglecting differences both in yield and biomass.

[Table 4 near here]

The parameters obtained from model calibrations were used for model validation. Measured and simulated results for validated data sets for Stitar are presented in Table 5 and for Cukurova in Table 6.

[Table 5 and 6 near here]

The results of seed yield validation for Stitar exhibited a very good match in the case of medium crop density (S_m), with variations ranging from 9.2% to 11%. However, in the case of low crop density (S_w), an excellent match was achieved in only one of the three years (1.4%), while in the other two years the deviations were 22.4% and 26.1%. Biomass was also better simulated for the S_m treatment (variation range 1.3% – 14.4%) than the S_w treatment (-11.7 – 26.5). In these two cases the model did not simulate well the drought impact in 2005/2006. The variations were much larger, compared to high crop density. The drought impact also resulted in large deviations of measured yields, as much as 30%, such that the simulated results were realistic and achievable.

At Cukurova, the results of the validated data set for both biomass and seed yield were very good and varied from 0 to ±13.9%. Such a good agreement was a result of the mild climate and irrigation applied as needed by the plant. It should also be noted that seed maturing was much more uniform at Cukurova than at Stitar.

The high value of the coefficient of determination, R^2=0.915, indicated an extremely good agreement of the simulated and measured seed yields. Larger variations were noted at Stitar, compared to Cukurova, as corroborated by R^2=0.617. It should be remembered that the object of this research was Italian ryegrass for seed, such that the model generated good predictions of seed yields under different climate conditions. This claim was substantiated by an analysis of statistical indicators. Namely, the high values of the Willmott index of

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agreement *d* of both the calibrated and validated data sets, for both study areas (>0.9), show that the AquaCrop model reliably predicted seed yields. Based on *NRMSE*, the variation was 11.67% at Cukurova and from 14.6% to 18.5% at Stitar. High variation in yield and biomass were obtained as well in both experimental research. For example, in Stitar yield varied from mean value 1.7% ± 15.4%, and biomass from 0.0% ± 28.5 %. These variations can be attributed to system errors in both study areas, which are difficult to avoid, such as: seed quantity, germination, soil homogeneity, irrigation non-uniformity, and the like. Indeed, higher *MBE* values at Stitar than at Cukurova indicated that there were several systemic errors, potentially a result of severe frost, occasional water-logging, non-uniform maturing, poor germination, etc.

Discussion

The starting point for the simulation of biomass and seed yields of Italian ryegrass was the fact that the AquaCrop model is water driven and that it is applicable to nearly all species, provided the necessary input data are available. The model was designed in such a way that yields of the studied crop can be studied after the basic files (climate, crop, soil, soil management, irrigation and initial soil moisture) are entered. For crops that have not been parameterized (no default file), such as Italian ryegrass, conservative parameters need to be tested in at least two different climate zones (Steduto et al. 2012). To ensure that the results are valid, parameterization and calibration were undertaken for plants well supplied with both water and nutrients, and plants affected by water stress. Validation was carried out for different crop densities obtained by different sowing rate, as well as under different growing conditions in moderate and Mediterranean climatic zones. The estimated normalized crop water productivity (14 g m^{-2}) was within the range of the default values set in the model for C_3 plants, such as Italian ryegrass (Raes et al. 2009). The adjusted WP for yield formation (25%) suited both varieties of Italian ryegrass and was consistent with the results of other

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studies of annual grasses (Riedo et al. 1998). Other conservative parameters, like Kcb, base and upper temperatures and water stress characteristics, were adjusted well for both zones.

The water supply for Italian ryegrass depended equally on precipitation and available soil moisture, but yield depended on crop density, cultivar characteristics and soil texture. For example, the yields at Cukurova were lower than at Stitar, regardless of more favorable climate conditions in the former case, partly because of the Italian ryegrass variety but also due to a poorer textural soil composition.

Initial soil moisture is very important for the simulation of biomass and seed yields with the AquaCrop model, especially if drought occurs during initial growth. In such a case, even a seemingly negligible amount of water (e.g. 82% of TAW instead of 83%) results in the model showing that it is not possible to achieve any yield or biomass, which is not true in nature. Of course, this can be due to either accelerated root development of exceedance of the selected initial root depth needed for survival, but also a result of model sensitivity. Research conducted to date has shown that the model provides lower-than-measured soil moisture levels in any case, as well as that it does not allow for soil drying below the wilting point (Araya et al. 2010; Mkhabela and Paul 2012). However, there are also reports of higher-than-measured values of soil water content (Farahani et al. 2009). This can be especially important when the model is applied to rainfed conditions and when it addresses climate change.

The results of Italian ryegrass yield simulations with an adequate water supply were very good, as the variation range was 0±13.9% in eight out of 10 treatments. Only two treatments registered grater variations, mostly due to unfavorable climate conditions (drought or severe frost). However, the biomass simulation, although highly effective in seven of 10 treatments, showed considerable variations under drought conditions (up to 40%), which later had a significant effect on statistical indicators. In any case, the effects of drought and ageing are the most difficult to adjust in models, regardless of their design principle. Consequently,

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the AquaCrop model, too, often does not produce good yield results if high water or temperature stress occurs in one of the growing seasons.

At Stitar, there was water stress in two of the three study years, to varying degrees: in one year at the beginning of growth but also for a few days during the flowering period, while in the other two years there was water stress both before and during flowering. Pre- and post-anthesis assimilate reserves play an important role in seed filling when the current photoassimilate supply is reduced (Griffith 2000). The stress was largely overcome at the seed yielding stage, owing to the higher photosynthetic power of grasses in regeneration (Duru et al. 2009), as well as their use of stored assimilates from the roots, stems and leaves (Slewinski 2012). This was demonstrated by the measured biomass and higher harvest index in those treatments. Namely, the model showed a higher-than-produced biomass even though it was possible to adjust HI in the case water or nutrient stress occurred, which was set in the model to reflect the measured data.

Research conducted to date shows that the AquaCrop model does not produce good results in the case of high water stress with maize (Heng et al. 2009; Hsiao et al. 2009), and barley (Araya et al. 2010), as well as with bambara groundnuts due to intra-landrace variability (Karunaratne et al. 2011), miscanthus (Stricevic et al. 2015), and wheat (Iqbal et al. 2014). Reported results of biomass simulation of perennial and annual grasses, using different models, show variations similar to those encountered in the present research, largely up to ± 10% and occasionally greater than 40%, not as a consequence of water stress but measured data inaccuracies, on the one hand, and model shortcomings on the other (McCall and Bishop-Hurley 2003). The high value of the coefficient of determination (R^2>0.9) in the biomass and seed yield simulation (of R^2=0.99 for Cukurova and 0.72 for Stitar) indicates that AquaCrop is a more reliable model than SOILN (Blombäck and Eckersten 1997) or the improved McCall herbage model (Romera et al. 2009), for grass growth simulation.

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Considering the reliability of the model via other statistical indicators, it was clear that AquaCrop produced more reliable predictions of Italian ryegrass biomass and seed yields where the winter climate was mild and there was adequate water supply, compared to moderate climates and rainfed conditions. The model also predicted seed yields better than biomass in both study areas, corroborated by the high Willmott index of agreement (d>0.916), NRMSE in the range from 11.7 to 18%, and MBE from -0.03 to 0.124 for the calibrated and validated data sets. Model much better simulate seed yield and biomass in high crop density than in medium and low crop density treatments. It is important to note that the model can be used even if limited input data are available. Although numerous other models have produced good crop yield simulation results, compared to them, this model is simpler, requires fewer input data, is generally available, and is deemed reliable for seed yield predictions only in high crop density. Additional validation data sets from different climatic and soil conditions are needed to test the model to be used in planning different sowing rate and seed production.

Acknowledgments

The paper was produced within the scope of the TR 37005 Project funded by the Serbian Ministry of Education and Science. The authors would like to thank editor and anonymous reviewers whose comments and suggestions resulted in significant improvements to this paper.

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Table 1. Main weather characteristics and irrigation depths during the growing cycles at Stitar and Cukurova

Study area	Year	Growing cycle (days)	Growing degree (°C)	Precipitation (mm)	Evapotranspiration (mm)	Irrigation depth (mm)
Stitar	2003/2004	266	2397	491	386	-
	2004/2005	242	2003	542	363	-
	2005/2006	264	2416	381	296	-
Cukurova	2002/2003	257	3850	436	415	100
	2003/2004	259	3847	488	380	150
	2003/2004	247	3858	488	352	120
	2004/2005	243	3852	354*	374	40*

*Good precipitation distribution throughout the growing cycle.

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Table 2. Input parameters for Italian ryegrass in two study areas

Parameters	**Value**			
	Stitar, Serbia			**Cukurova, Turkey**
	High crop density	**Medium crop density**	**Low crop density**	**High crop density**
Base temperature, ºC		5		5
Cut-off temperature, ºC		30		30
Crop coefficient (κ_{cb}) at CC=100%		1.05		1.05
Water productivity (WP), g·m^{-2}		14		14
WP adjustment for yield formation		25 %		25 %
Maximum effective rooting depth, m		0.7		0.8
Harvest index (HIo), %		15		8
Water stress				
– Canopy expansion (p_{upper}); (p_{lower}); shape factor		0.0; 0.35; 2.5		0.0; 0.35; 2.5
– Stomatal closure (p_{upper}); (shape)		0.25; 2.0		0.25; 2.0
– Early canopy senescence (p_{upper}); (shape factor)		0.45; 2.0		0.45; 2.0
– HI formation				
– Before flowering		Increase in HI – 6%		Increase in HI – 6%
– During flowering		Positive effect (a=1.2)		Positive effect (a=1.2)
– During yield formation		Small negative		Small negative
– Aeration stress (%)		5%		5%
Initial canopy cover (CCo), %	1.2	0.9	0.8	0.1
Canopy expansion (CGC), % per day	3.7	3.7	3.7	4.9
Maximum canopy cover (CCx), %	85	75	65	75
Canopy decline (CDC), % per day	17	17	17	17
Effect of canopy shelter in late season	95	75	60	95

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Table 3. Main characteristics of Italian ryegrass (*Lolium multiflorum*) seed crop

Study area	**Sowing date**	**Germination**	**Flowering**	**Harvesting**	**Row spacing (cm)**		
					High	Medium	Low
Stitar	13.10.2003	24.10.2003	15.5.2004	6.7.2004	20	40	60
	30.10.2004	16.11.2004	21.5.2005	30.6.2005	20	40	60
	13.10.2005	1.11.2005	28.5.2006	5.7.2006	20	40	60
					crop density		
Cukurova	1.10.2002	12.10.2002	25.4.2003	15.6.2003	15, 20, 25, 30		
	4.10.2003	17.10.2003	5.5.2004	21.6.2004	15, 20, 25, 30		
	10.10.2003	20.10.2003	18.4.2004	14.6.2004	30		
	11.10.2004	28.10.2004	27.4.2005	28.6.2005	30		

Table 4. Simulation results for calibration data sets of Italian ryegrass and deviation from measured values of total biomass and yield (with stdev)

Year	Yield			Biomass		
	Measured (Mg ha^{-1})	Simulated (Mg ha^{-1})	Deviation (%)	Measured (Mg ha^{-1})	Simulated (Mg ha^{-1})	Deviation (%)
Stitar						
2003/2004	0.87±0.04	1.11	27.1	7.50±1.1	7.46	-0.5
2004/2005	1.39±0.05	1.51	9.0	8.74±0.7	9.08	3.9
2005/2006	0.94±0.08	0.95	1.2	5.55±0.8	6.73	21.3
Cukurova						
2004/2005	0.35±0.02	0.35	0.0	4.57±0.46	5.02	4.6

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Table 5. Simulation results for validated data set of measured Italian ryegrass yield and biomass for two different densities at Stitar (with stdev)

Year	Yield						Biomass					
	Medium crop density			Low crop density			Medium crop density			Low crop density		
	Measured ($Mg\ ha^{-1}$)	Simulated ($Mg\ ha^{-1}$)	Deviation (%)	Measured ($Mg\ ha^{-1}$)	Simulated ($Mg\ ha^{-1}$)	Deviation (%)	Measured ($Mg\ ha^{-1}$)	Simulated ($Mg\ ha^{-1}$)	Deviation (%)	Measured ($Mg\ ha^{-1}$)	Simulated ($Mg\ ha^{-1}$)	Deviation (%)
2003/2004	0.91±0.12	1.01	10.7	1.22±0.07	0.91	-26.1	8.17±0.69	7.00	-14.4	6.94±0.44	6.11	-11.7
2004/2005	1.59±0.18	1.38	-11.0	1.50±0.05	1.16	-22.4	8.16±0.25	8.27	1.3	5.97±0.37	7.54	26.5
2005/2006	0.79±0.09	0.86	9.2	0.77±0.08	0.78	1.4	3.31±1.01	6.00	81.3	3.89±0.43	5.43	40.5

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Table 6. Simulation results for validated data set of measured yield and biomass of Italian ryegrass grown at Cukurova (with stdev)

	Yield			Biomass		
Year	High crop density			High crop density		
	Measured (Mg ha^{-1})	Simulated (Mg ha^{-1})	Deviation (%)	Measured (Mg ha^{-1})	Simulated (Mg ha^{-1})	Deviation (%)
2002/2003	0.27±0.02	0.23	-12.7	3.49±0.26	3.97	13.6
2003/2004	0.37±0.06	0.32	-13.9	4.62±0.55	4.61	-0.3
2003/2004	0.28±0.02	0.27	-1.4	3.75±0.24	4.01	6.8

Table 7. Statistical variables of calibrated and validation data sets for two study areas

Variables	Calibration data set - Stitar		Validation data set			
			Yield		Biomass	
	Yield	Biomass	Stitar	Cukurova	Stitar	Cukurova
RMSE (Mg ha^{-1})	0.15	0.71	0.21	0.04	1.54	0.31
NRMSE (%)	14.6	9.76	18.47	11.67	25.40	7.87
MBE	0.12	0.49	-0.11	-0.03	0.66	0.24
d	0.94	0.75	0.92	0.98	0.08	0.86
R^2	0.92	0.94	0.90	0.92	0.72	0.99

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