

# Application of the AquaCrop model to simulate the biomass of *Miscanthus x giganteus* under different nutrient supply conditions

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## Abstract

There are conflicting opinions about the need to fertilize *Miscanthus* and, also, the question has been raised whether *Miscanthus* should be irrigated, especially if water resources are limited. Crop growth modeling can help answer such questions. In this article the FAO AquaCrop water-driven model was selected to simulate *Miscanthus* biomass under different nutrient and water supply conditions. The article reports the outcomes of 6-year experiments with *Miscanthus* on two locations in Serbia: Zemun, where three fertilizer treatments were applied ( $N_i - 100 \text{ kg ha}^{-1}$ ,  $N_{opt} 50 \text{ kg ha}^{-1}$  and  $N_f$  nonfertilized), and Rajka, where only  $N_i 100 \text{ kg ha}^{-1}$  was applied. Model calibration focused on the measured data (root depth, crop phenology, and the above-ground biomass by year of growth). Calibration results showed a very good match between measured and simulated values. The largest and only significant difference was noted in 2008, when the crop was establishing and exhibited uneven radication. The simulation results for the next 5 years showed a variance from  $-4$  to  $5.7\%$ , believed to be a very good match. A high coefficient of determination ( $R^2 = 0.995$ ) and high Willmott index of agreement (0.998) were also indicative of a good match between simulated and recorded biomass yields. The measured and simulated results for validated datasets at both locations were good. The average RMSE was  $2.89 \text{ Mg ha}^{-1}$ ; when compared to the deviations noted at the test site itself, it was apparent that they were smaller in all the years of research except the first year. The index of agreement was 0.97 and the coefficient of determination  $R^2 0.947$ . The AquaCrop model can be used with a high degree of reliability in strategic planning of *Miscanthus* cultivation in new areas, under different nutrient and water supply and local weather and soil conditions.

**Keywords:** AquaCrop, biomass, *Miscanthus x giganteus*, modeling, nutrient stress, water stress

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## Introduction

*Miscanthus* (*Miscanthus x giganteus* Greef et Deu) is a perennial grass crop whose entire above-ground biomass can be used as biofuel, to produce bioenergy through combustion. It is a tall  $C_4$  grass with a lifespan of 15–20 years; it is harvested each year and its potential above-ground biomass up to  $49 \text{ Mg ha}^{-1}$  (Zub & Brancourt-Hulmel, 2010), which is a precondition for an economical biofuel. It is believed that land availability will be a limiting factor for biofuel crop cultivation (Bessou *et al.*, 2011). Research conducted to date reports that *Miscanthus* can be grown on all types of soils (Dale *et al.*, 2000). This places it in the category of potentially preferred crops for cultivation on damaged, degraded soils, or in ecologically marginal areas, which cannot be used for food production (Dale *et al.*, 2011).

Research on chromic luvisol in the United Kingdom has shown that *Miscanthus* biomass yields do not increase with the addition of nitrogen fertilizers, but it is necessary to fertilize to avoid nitrogen depletion in the soil (Christian *et al.*, 2008). In Italy, *Miscanthus* reportedly achieved  $14.5 \text{ Mg ha}^{-1}$  yields without the application of fertilizers and at reduced irrigation levels (25% ET), but increased yields by as much as 100% when well supplied with water and nutrients (Cosentino *et al.*, 2007). Even though research conducted in Europe and the United States has shown that the production of *Miscanthus* is cost-effective (Khanna *et al.*, 2008), it is not grown in Serbia on a large scale. Surveys revealed only some twenty relatively small areas, although the agro-climatic conditions for this crop are favorable (Dzeletovic *et al.*, 2013). According to official statistics, there are many ecologically marginal areas in Serbia that can be used to grow *Miscanthus*, but the limiting factors are summer water deficit and lack of nutrients.

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The provision of bioenergy is in the public interest and the central government needs to ensure the basic preconditions for a production that will be competitive in the marketplace. This is generally achieved through subsidies. However, to determine appropriate subsidy levels, it is necessary to impartially assess the impact of drought and fertilization levels on yields and make strategic decisions for the future. Today, this is made possible by a variety of plant production simulation models, such as: FAO AquaCrop (Steduto *et al.*, 2009); WOFOST (Supit *et al.*, 1994), SWAT (van Dam *et al.*, 1997), CERES (Ritchie *et al.*, 1985), Cropsyst (Stöckle *et al.*, 2003), adaptive artificial neural networks, and a number of other models. Although they differ in essence, all these models are able to simulate plant production with a higher or lower degree of accuracy (Zand-Parsa *et al.*, 2006; Abraha & Savage, 2008; Park *et al.*, 2005; Ma *et al.*, 2006). Several models have been used to simulate Miscanthus biomass. Clifton-Brown *et al.* (2000) developed a simple model based on radiation and temperature, to determine the potential productivity of Miscanthus in Ireland. A simple predictive model was applied in England and Wales, founded upon temperature totals and incident radiation only for well-established crops, when they reach their maximum production capability – after 5–6 years (Price *et al.*, 2004), but contrary to the previous model, the impact of water stress on yield was addressed. As such, these models cannot be used to predict the biomass of younger plants. Clifton-Brown *et al.* (2004) developed the MISCANMOD model, and Hastings *et al.* (2009) upgraded it (now MISCANFOR), through a better description of temperature and water stress on radiation use efficiency. The application of this model led to the conclusion that although Miscanthus can be highly productive in southern Europe, a  $\pm 20\%$  variation depends on the weather and soil conditions prevailing at a given site. Miguez *et al.* (2009) developed the BioCro model which is based on the WIMOVAC mode (Humphries & Long, 1995), which was adapted and parameterized for Miscanthus at a location in England and tested (validated) for biomass yields at several sites across Europe and United States (Miguez *et al.*, 2012). This model can predict biomass yields during the growing season at different locations in Europe. They also used parameter estimation capabilities and graphical procedures to evaluate the agreement between observed and simulated data. Tze Ling *et al.* (2010) was applied the SWAT model to examine the potential impact of river water loaded with nitrogen on Miscanthus, instead of conventional crops. Extensive experimental field data are necessary to parameterize these models for different ecological conditions, which is often their significant shortfall as in many countries it is not possible to undertake numerous measurement

due to a lack of finance and also because of the plants habitat.

To provide for a programmed expansion of the production of Miscanthus as a new crop, it is necessary to prepare sound conditions for high and stable yields. Soil fertility can be achieved by agro-technical measures, but the key issue is sound management of water resources. Namely, a crop can be grown without irrigation in Serbia, because there are frequent years with an average precipitation level of 300–400 mm, which, along with soil moisture reserves, ensures a sufficient amount of water for high yields (Stricevic & Djurovic, 2013).

Models such as AquaCrop target a wide circle of users, who need information about biomass production or yields of crops grown under different water and nutrient supply conditions. If the correlations between soil, water, plant, and atmosphere are well known, it is relatively easy to obtain needed climate, soil water capacity, texture, soil salinity, crop parameters, and agro-technology data (irrigation scheduling, mulch, irrigation method, soil fertilization) and use the model. Based on model calibration and validation for local conditions, many researchers suggest that the model can be used to simulate plant production for practical purposes such as for better water management practices, sowing scheduling, plant density, etc. (Todorovic *et al.*, 2009; Geerts *et al.*, 2010; Stričević *et al.*, 2011; Mkhabela & Bullock, 2012; Wellens *et al.*, 2013). The objective of this article is to test, using the FAO AquaCrop model, the possibility of predicting above-ground biomass yields of *Miscanthus × giganteus* (Greef et deu) grown under different nutrient supply conditions, but with different levels of natural water supply (rainfed conditions) for both developing and fully established plants.

## Materials and methods

### Experimental data

The input data needed for the FAO AquaCrop model were collected at two test sites of the Institute for the Application of Nuclear Energy (INEP): in Zemun (44°49' N latitude; 20°17' E longitude) and Ralja (44°22' N, 20°57' E), both in Serbia (South East Europe).

To characterize the climate of the test sites, meteorological data recorded over a period of 47 years (1981–2010) from the nearest meteorological stations (at Surčin for Zemun and Smederevska Palanka for Ralja) were used. Both sites feature a moderate climate, with four distinct seasons. Minimum, maximum, and mean annual precipitation totals at Zemun were 351, 1086, and 642 mm, respectively. The mean annual temperature was 11.7 °C. The mean annual air humidity was 72% and the wind speed at a height of 2 m was 1.7 m s<sup>-1</sup>. Tmean, Tmin, and Tmax at Ralja were 11.5, 6.3, and 17.4 °C, respectively. The mean, minimum, and maximum precipitation totals were 635,

375, and 864 mm, respectively. The mean annual relative air humidity was 72% and the wind speed at 2 m was  $1.6 \text{ m s}^{-1}$ . The average growing degree days (GDD, with a  $0 \text{ }^{\circ}\text{C}$  base) was 3288  $^{\circ}\text{C}$ .

The soil at Zemun is represented by highly calcareous loam, overlying a mollic horizon of alkaline chernozem soil. The deep, dark grayish-brown, nearly black mollic horizon features a loamy texture. The soil structure is crumbly to dusty. Bulk density was found to range from  $1.33$  to  $1.45 \text{ g cm}^{-3}$ . Air porosity varied from 13.1 to 20.5%. The mean volumetric soil moisture across the soil profile at field capacity and the wilting point were 33.7% and 16.5%, respectively. The total available soil water (TAW) was calculated from the difference between field capacity and wilting point, which was  $170 \text{ mm m}^{-1}$ . The soil was mildly alkaline (pH of  $\text{H}_2\text{O} = 7.3$ ), while the content of organic carbon was 1.71% and that of nitrogen 0.14%.

The soil at Rajla is brown earth (eutric cambison according to FAO classification). The texture is that of light clay, the hydro physical and chemical properties were less favorable than at Zemun, and there was a restrictive layer at a depth of 1.1 m. The mean volumetric soil moisture across the soil profile at field capacity and the wilting point were 42.6% and 21.8%, respectively. The total available soil water (TAW) was calculated from the difference between field capacity and wilting point, which was  $208 \text{ mm m}^{-1}$ . The soil was mildly acidic (pH in  $\text{H}_2\text{O} = 5.4$ ), with a moderate humus content (total organic C 1.38%) and a relatively low nitrogen content (N 0.11%), such that fertilizing was necessary.

The experiments were based on a randomized block design with three treatments and three replications in six consecutive years (2008 – 2013) at Zemun. The size of each plot was  $4 \text{ m} \times 5 \text{ m}$ .

- Treatment  $N_f$  (0  $\text{kg ha}^{-1}$  N-P-K added);
- Treatment  $N_{\text{opt}}$  – 50  $\text{kg ha}^{-1}$  N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O;
- Treatment  $N_l$  – 100  $\text{kg ha}^{-1}$  N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O.

At Rajla, there was only one type of treatment,  $N_l$  in three replication, because the soil was poor in nutrients. The size of each plot was also  $4 \text{ m} \times 5 \text{ m}$ .

- Treatment  $N_l$  – (100  $\text{kg ha}^{-1}$  N-P-K).

The planting density at both sites was 2 rhizomes  $\text{m}^{-2}$ . Commercial fertilizer (NPK 15 : 15 : 15) was used to provide mineral nutrients at this site.

Irrigation was applied only during the first year of research, in all scenarios. To ensure sufficient amounts of readily available water for the growth of Miscanthus, irrigation was applied four times and a total of 40 mm of water was added.

Miscanthus was planted on previously cultivated soil at a depth of 0.1 m on 13 May 2008, in such a way as to achieve the desired density (2 rhizomes  $\text{m}^{-2}$ ). Uneven radication and growth were noted during the first year. At that time Miscanthus developed roots more rapidly than the above-ground biomass. It steadily increased yields over the first 4 years, while in the fifth year the yields declined. After the second year of the study period, Miscanthus generally began its vegetative growth on 14 April ( $\pm 2$  days), ending around 15 October. Each year crop development lasted 15 days, the period up to the

formation of the maximum canopy cover was 90 days and senescence was noted on the 174th day after rejuvenation. Flowering always took place after the autumn equinox – on the 166th day. Rapid leaf drying was noted on the 188th day, at which time the biomass yield was maximal.

### 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 article will mention only those parameters that are relevant to biomass and yield simulation of Miscanthus.

Climate input data included: daily value of reference evapotranspiration calculated by the FAO Penman–Monteith method (Allen *et al.*, 1998), daily values of maximum and minimum air temperatures, daily sums of precipitation during the period of research, irrigation depth, and dates of irrigation (irrigation only in the year 2008). A temperature stress for crop development and biomass production of  $2 \text{ }^{\circ}\text{C}$  and a heat stress of  $35 \text{ }^{\circ}\text{C}$  were specified (Hsiao *et al.*, 2009; Miguez *et al.*, 2009). It was noted that biomass yields did not vary even if the base temperature of  $0 \text{ }^{\circ}\text{C}$  was retained, which was as expected because during the growing season temperatures lower than  $2 \text{ }^{\circ}\text{C}$  were recorded at the end of vegetation (around 15 October). The lowest value of the harvest index, 2%, was specified, although that derived from the experiments was even lower ( $<0.5\%$ ). It was also important to take into account the soil moisture level just before rejuvenation. Serbia's climate is such that the soil is generally well wetted across the profile (even to a depth of more than 2 m), due to snow melt.

Given that AquaCrop, Version 4.0, does not contain a default file for Miscanthus, the starting point of the calibration process included the entry of: crop density, C<sub>4</sub> crop option, postwinter/postdormancy crop transplantation option (instead of rejuvenation), and recorded crop growth stages.

The model was calibrated through an iterative process, using measured crop growth variables, observed phenological stages, parameters estimated from available data, and derived growing coefficients of well nutrient ( $N_l$ ) and well water supplied Miscanthus in the years 2008, 2009, and 2010, and for water limiting conditions in 2011 and 2012 ( $N_l$ ).

Given that Miscanthus is a crop that grows for 3–5 years before it reaches its highest productivity (Price *et al.*, 2004), certain parameters varied over the first years (e.g. root depth, crop coefficient  $k_c$ , maximum canopy cover), while those in the fifth and sixth years were the same as in the fourth year. The majority of parameters measured the same values throughout the study period, such as conservative parameters (WP, base temperature, harvest index, aeration stress, nutrient stress). The model was validated using data derived from the following scenarios: near optimal ( $N_{\text{opt}}$ ) treatment and no fertilizer treatment ( $N_f$ ) at Zemun, and nutrient nonlimiting supply ( $N_l$ ) at Rajla.

*Nutrient stress.* The AquaCrop model does not address in detail the effect of fertilizer application on plant growth. AquaCrop provides default adjustments of the pivotal crop parameters for several limiting fertility categories, ranging from near

optimal to poor. The adjustments are multipliers, used to reduce: (i) CGC; (ii) CCx; (iii) CC – from the time CCx is reached to maturity, but only gradually; and (iv) WP' (Steduto *et al.*, 2012). CC is the fractional coverage of the soil by the canopy at time  $t$ , CCo is initial CC (at  $t = 0$ ) also in fraction, and CGC is canopy growth coefficient in fraction or percentage of existing CC at time  $t$ . WP is the water productivity parameter (kg of biomass  $m^{-3}$  of water transpired). Using these rules as guidance, biomass yields with treatment  $N_f$  (100 kg  $ha^{-1}$  N-P-K) were compared with treatments that involved smaller amounts of fertilizer. The ratio was almost the same each year:

- $N_{opt}/N_f = 0.93$ , or a 7% reduction
- $N_f/N_f = 0.74$ , or a 26% reduction

As such, model calibration was aimed at reducing CGC, CCx and WP, as follows:

$N_{opt}$  treatment: biomass production – near optimal; maximum canopy cover (CCx) close to reference level (observed biomass reduction 7%); and effect on water productivity 12%.

$N_f$  treatment: biomass production moderate; maximum canopy cover (CCx) slightly reduced (observed biomass reduction around 26%); and effect on water productivity 46%. The input parameters are shown in Table 1 by year. However, it was not enough to only reduce the plant parameters. It was necessary to also select the right soil fertility option, with corresponded

to fertilizer application. There were two options in this research:

#### Soil potential.

- Optimal – for treatment  $N_f$  (100 kg  $ha^{-1}$  N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O)
- Near optimal – the selection of this option results in a biomass yield expectancy of 80% of potential yield (chernozem-fertile soil);

Although *Miscanthus* generally achieves high yields even when its water supply is low, it responds very well to irrigation, increasing biomass yield by as much as 100% (Cosentino *et al.*, 2007). In Serbia's ecological circumstances, *Miscanthus* had enough water during the first 3 years of research, but it was under water stress over short periods in the fourth, fifth, and sixth years. To check whether the model generated realistic biomass levels when the water supply was nonlimiting, the file called 'Generation of irrigation schedule' was used and the option 'Replenish when 80% readily available water depleted' was selected. As such, if irrigation is applied, the dates of irrigation and amounts of water need to be entered so that they are accounted for in the water balance. In the present example, instead of entering the dates of irrigation and amounts of water, the model determined how much water was needed and when, to achieve potential yields.

**Table 1** Input parameters for *Miscanthus* in six consecutive years

Parameters	Years					
	2008	2009	2010	2011	2012	2013
Base temperature, °C	2	2	2	2	2	2
Cutoff temperature, °C	35	35	35	35	35	35
Initial canopy cover (CCo),%	0.1	0.1	0.1	0.1	0.1	0.1
Canopy expansion (CGC),% per day	12.5	11.2	12.3	12.4	12.4	12.4
Maximum canopy cover (CCx),%	65	68	95	98	98	98
Canopy decline (CDC),% per day	11.5	11.5	15.4	16.5	16.5	16.5
Crop coefficient ( $k_{cb}$ ) at CC = 100%	0.8	0.8	0.95	1.05	1.05	1.05
Maximum effective rooting depth, m	0.39	0.39	0.7	2.30	2.5	2.5
Water productivity (WP), g $m^{-2}$	34	34	34	34	34	34
Harvest index (Hlo),%	2	2	2	2	2	2
Water stress						
Canopy expansion	MS	MS	MT	T	T	T
Stomatal closure	MS	MS	MT	T	T	T
Early canopy senescence	MS	MS	MT	T	T	T
Aeration stress (%)	5	5	5	5	5	5
Nutrient stress						
Near optimal						
Effect on maximum canopy cover (CCx),%	60	63	85	92	92	92
Effect on reduced canopy expansion,%	3	3	3	3	3	3
Effect on water productivity,%	12	12	12	12	12	12
Nonfertilized						
Effect on maximum canopy cover (CCx),%	52	54	72	78	78	78
Effect on reduced canopy expansion,%	12	12	12	12	12	12
Effect on water productivity,%	46	46	46	46	46	46

Where: MS – default value for 'moderately sensitive to water stress'; MT – default value for 'moderately tolerant to water stress', and T – default value for 'tolerant to water stress'.

The same input data with the addition of irrigation water generated a yield of 42 Mg ha<sup>-1</sup>, which matched those recorded in Greece and Italy under irrigation and constraint free-conditions, in similar climatic circumstances and with similar crop densities (Cosentino *et al.*, 2007; Danalatos *et al.*, 2007).

### Data analysis

Three 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:

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

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, and the model's fit improves when RMSE tends toward zero.

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

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

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 simulates the studied parameter better as the value approaches 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  $R^2$  value, cannot indicate if the model overestimates or underestimates the value, so an additional test of model goodness was needed.

$$R^2 = \frac{\sum (M_i - \bar{M})(S_i - \bar{S})}{\sqrt{\sum (M_i - \bar{M})^2 \sum (S_i - \bar{S})^2}} \quad (3)$$

## Results

To provide more insight into the conditions in which Miscanthus grew, Table 1 shows the climate characteristics of both sites during the six-year experiment: the growing degree with a 0 °C base, precipitation sum, actual evapotranspiration (ETa), and irrigation. Table 2 shows the climate parameters for the duration of the experiment. One hand, the data indicate lower-than-average precipitation in 5 of 6 years, but on the other hand the growing seasons were warmer than average (DGG > 328 °C).

Since the period of growth of Miscanthus was 4–5 years, the model was calibrated for the first 4 years of research. No changes were made in the fifth and sixth years. Each year Miscanthus increased its above-ground biomass and root depth, so generally these

parameters were varied in the calibration process, as was the crop coefficient because water use increased. In the first 2 years Miscanthus formed rhizomes and root growth was slow. In the third year, there was enough moisture in the more fertile surface layer of soil, such that root depth was smaller than expected. The next 3 years were dry, so in search for water the roots considerably increased their depth (up to 2.3 m), which was consistent with data collected from other experiments (Neukirchen *et al.*, 1999; Riche & Christian, 2001).

The simulation results for Miscanthus using calibrated datasets are presented in Table 3. The calibration results show a very good match between measured values and those simulated by the model. The largest and only significant difference of 60% was noted in 2008, when Miscanthus was planted. In view of the fact that the crop was planted 1 month after the optimal time (and irrigated), it exhibited uneven germination and radication, which may account for this large difference. The planting density of 2 m<sup>-2</sup> was high enough to offset the losses; canopy closure was achieved in the later years and the model worked well. The simulation results for the remaining 45 years varied from –4 to 5.7%, deemed to be a virtually insignificant disagreement. The high coefficient of determination ( $R^2 = 0.995$ ) reflects a very good agreement of simulated and measured biomass yields.

The measured and simulated results for validated datasets of Miscanthus grown at different levels of nutrient supply are presented in Table 4, and for the Ralja location in Table 5. At Ralja, the simulation results for years 3 through 6 were very good, exhibiting deviations from –5 to 16.3%; however, the deviations in the first 2 years were considerable. Table 4 shows that the standard deviation of 2010 yield was ±9.5 Mg ha<sup>-1</sup>, or more than 60% in 2010, and the simulation suggested a deviation of –47.9% from the measured average yield; this is a clear indication that the simulated yields were realistic and achievable. The biomass yield simulation results for 2012 also indicated large deviations (–70.5%), although the experiments recorded a lower yield variation (± 3.2 Mg ha<sup>-1</sup> or more than 30%). Such a large variance can be attributed to poor precipitation distribution and water stress in August, when there was no rainfall.

At Zemun, for the limited nutrient supply scenario, the simulation results in nine of 12 cases were good, exhibiting negligible departures in the range from 16.4 to –16.4%. Major deviations were noted only in the first 2 years of research, at the time of radication. As in Ralja, the variation in measured yields was large, such that simulated yields did not exhibit an unrealistic deviation from actually recorded yields.

**Table 2** Main weather characteristics, actual evapotranspiration and irrigation depth during growing cycles

Year	Growing cycle (days)	Growing degree* (°C)		Precipitation sum (mm)		Actual evapotranspiration (mm)		Irrigation depth (mm)
		Surčin	Ralja	Surčin	Ralja	Surčin	Ralja	
2008	158	4251	2826	265	222	265	300	40
2009	187	3764	3274	328	364	313	372	–
2010	187	3560	3124	431	473	429	518	–
2011	187	3741	3230	220	245	530	468	–
2012	187	3539	3395	220	337	524	541	–
2013	187	3662	3538	217	359	420	397	–

\*Growing degree calculated for 0 °C base.

**Table 3** Simulation results for calibrated datasets of Miscanthus (fully fertilized during five consecutive years and with supplementary irrigation only in 2008), and deviation from measured values of total biomass with SD

Year	Fully fertilized		
	Measured (Mg ha <sup>-1</sup> )	Simulated (Mg ha <sup>-1</sup> )	Deviation (%)
2008	0.3 ± 0.1	0.13	60.6
2009	4.5 ± 1	4.5	0.0
2010	20.2 ± 1.3	21.0	–4.0
2011	28.3 ± 0.4	26.7	5.7
2012	21.9 ± 1.4	21.0	3.8
2013	19.98 ± 0.2	19.7	1.4

The coefficient of determination ( $R^2$ ) show that the model simulated biomass yield with a high degree of reliability. Somewhat larger deviations were noted at Ralja, where the physicochemical properties of the soil were less favorable, compared to Zemun where Miscanthus grew on very fertile soil (chernozem). It should be noted that no effect of fertilizer application on Miscanthus yields was noted in the sixth year. As a matter of

fact, the highest yields were recorded with no fertilizer application.

Table 6 summarizes the statistical parameters of the model calibration and validation datasets for all years of research. The coefficients of determination exhibit a very good match in both calibrated and validated datasets. The good match was corroborated by the Willmott index of agreement ( $d$ ), whose values of 0.998 and 0.973 for the two datasets were close to one, indicating an excellent agreement.

## Discussion

The starting point for the Miscanthus biomass simulation was the fact that the AquaCrop model is water driven and that it can be used for virtually any plant species, if sufficient input data are available. The model has been designed such that basic files (climate, crop, soil, soil management, irrigation, and initial soil moisture) can be entered and crop yields predicted each year. As such, given that the models were calibrated for the first 4 years of Miscanthus growth, they could be used at other locations as well, which was done in the present research.

**Table 4** Simulation results for validated datasets of measured biomass for Miscanthus on that of near optimally fertilized and non-fertilized, grown in Zemun (including standard deviation)

Year	Treatment $N_{opt}$			Treatment $N_f$		
	Measured (Mg ha <sup>-1</sup> )	Simulated (Mg ha <sup>-1</sup> )	Deviation (%)	Measured (Mg ha <sup>-1</sup> )	Simulated (Mg ha <sup>-1</sup> )	Deviation (%)
2008	0.3 ± 0.1	0.13	54.1	0.2 ± 0.1	0.13	33.5
2009	4.7 ± 1.4	4.4	4.7	2.2 ± 0.8	4.4	–104.6
2010	18.6 ± 7.0	17.6	5.6	14.8 ± 3.4	17.3	–16.4
2011	26.1 ± 12.6	24.9	4.5	23.7 ± 4.9	24.6	–3.8
2012	19.6 ± 6.9	19.95	–1.6	19.5 ± 2.6	19.7	–1.2
2013	19.8 ± 7.2	19.01	3.5	22.3 ± 1.3	18.7	16.4

**Table 5** Simulation results for validated datasets of measured biomass for fully fertilized *Miscanthus*, grown in Ralja site

Year	Treatment $N_1$		Deviation (%)
	Measured ( $\text{Mg ha}^{-1}$ )	Simulated ( $\text{Mg ha}^{-1}$ )	
2008	$1.0 \pm 0.8$	1.1	-5.0
2009	$7.7 \pm 6.5$	7.7	0.3
2010	$15.5 \pm 9.5$	22.9	-47.9
2011	$18.9 \pm 6.5$	18.6	1.7
2012	$11.3 \pm 3.2$	19.2	-70.5
2013	$10.8 \pm 5.5$	12.6	16.3

**Table 6** Root mean square error (RMSE), index of agreement ( $d$ ), and  $R^2$  for measured and simulated above-ground *Miscanthus* biomass

Variables	Calibration dataset	Validation dataset
RMSE ( $\text{Mg ha}^{-1}$ )	0.896	2.89
$d$	0.998	0.973
$R^2$	0.995	0.947

Water availability for *Miscanthus* depended equally on precipitation and accumulated soil moisture, such that yields were generally a reflection of root depth and soil characteristics. For example, the yields recorded at Ralja were lower than those achieved at Zemun because of the restrictive soil layer in the former case and the inability of *Miscanthus* to develop deeper roots. The importance of soil and root depth for the simulation of plant production has been corroborated by other researchers (Raes *et al.*, 2009).

Each year, at the time of *Miscanthus* rejuvenation, uneven budding and biomass growth were noted. During the growing season these differences decreased in some fields, but not in others. This was the reason for the high standard deviation of recorded biomass yields. Viewed in this manner, it was apparent that nearly all simulated yields were realistic and achievable in natural circumstances. Taking into account that the RMSEs generated by the model were  $0.896 \text{ Mg ha}^{-1}$  for the calibrated dataset and  $2.89 \text{ Mg ha}^{-1}$  for the validated dataset, they compare well with the results derived from other *Miscanthus* research. Namely, Miguez *et al.* (2012) used the BioCro model at three sites and recorded greater deviations (RMSE  $4.66 - 12.2 \text{ Mg ha}^{-1}$ ), but only well-established plants, with a larger biomass, were observed and the departures were therefore greater. Similar deviations were noted in barley biomass predictions applying the AquaCrop model in Ethiopia (Berhanu *et al.*, 2012), where a large standard deviation of biomass was registered even in the field.

When model reliability is assessed via the Willmott index of agreement, the AquaCrop model tends to be more reliable for predicting *Miscanthus* yields in different water and nutrient supply conditions, compared to the BioCro model where the index of agreement at three locations over three years of research (*Miscanthus* roots already well-established) exhibited a considerably lower value  $-0.75$  (Miguez *et al.*, 2012).

The impacts of drought and aging are the most difficult parameters to adjust on a model, regardless on which principles it is based. Even the AquaCrop model often fails to generate good yield results if there was substantial water stress during the growing season. In the present research such stress occurred at Ralja, at a time when the plants were well established and when rainfall failed in the warmest month of August. According to Miguez *et al.* (2009), the WIMOVAC model exhibits certain shortfalls with regard to yield prediction when there is severe water stress. Research conducted to date with maize shows that the AquaCrop model does not generate good results if there is severe stress (Heng *et al.*, 2009; Hsiao *et al.*, 2009), with regard to barley (Araya *et al.*, 2010), and bambara groundnuts due to the intralandrane variability (Karunaratne *et al.*, 2011).

Although past models except BioCro (Miguez *et al.*, 2012) have not taken into account *Miscanthus* biomass simulation during the period of plant development, this research shows that it is possible to parameterize the AquaCrop model for both developing and fully established plants. The simulated data derived and analyzed here suggest that the AquaCrop model can be used with a high degree of reliability in both day-to-day management and strategic planning of *Miscanthus* cultivation in new areas, under different nutrient and water supply and local weather and soil conditions. Input data can readily be obtained from the field and the model is relatively easy to use. Had *Miscanthus* had an ample water supply in the 4th–6th years of the present research, it would have achieved the yields generally recorded in South East Europe, in similar climates and with comparable crop densities (Cosentino *et al.*, 2007; Danalatos *et al.*, 2007), attesting to our belief that the model can effectively be used to simulate yield of *Miscanthus* grown on different soils, water supply, and climatic condition. This fact is important because the model can be applied even if limited input data are available. Although many 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 highly reliable for simulating biomass, yield, and water demand. As such, it is recommended for application under different climatic conditions.

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