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There is no study on yield response of rice to salinity stress using the FAO AquaCrop model which was released in 2009. However, coastal areas in the world are affected by salinity. Furthermore, rice is an important staple food crop, particularly in south and southeast Asia. The parameterized model, especially the crop response versus salinity stress curve developed in this study will be useful to crop modelers, agriculturists, environmentalists and water managers, among others, to assess the potential impacts of climatic and hydrologic changes on rice yield and hence food security in many coastal regions of the world.

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PAPER

# Simulating yield response of rice to salinity stress with the AquaCrop model

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The FAO AquaCrop model has been widely applied throughout the world to simulate crop responses to deficit water applications. However, its application to saline conditions is not yet reported, though saline soils are common in coastal areas. In this study, we parameterized and tested AquaCrop to simulate rice yield under different salinity regimes. The data and information required in the model were collected through a field experiment at the Bangladesh Agricultural Research Institute, Gazipur. The experiment was conducted with the BRRI Dhan28, a popular boro rice variety in Bangladesh, with five levels of saline water irrigation, three replicates for each level. In addition, field monitoring was carried out at Satkhira in the southwest coastal region of Bangladesh to collect data and information based on farmers' practices and to further validate the model. The results indicated that the AquaCrop model with most of its default parameters could replicate the variation of rice yield with the variation of salinity reasonably well. The root mean square error and mean absolute error of the model yield were only 0.12 t/ha and 0.03 t/ha, respectively. The crop response versus soil salinity stress curve was found to be convex in shape with a lower threshold of 2 dS/m, an upper threshold of 10 dS/m and a shape factor of 2.4. As the crop production system in the coastal belt of Bangladesh has become vulnerable to climate induced sea-level rise and the consequent increase in water and soil salinity, the AquaCrop would be a useful tool in assessing the potential impacts of these future changes as well as other climatic parameters on rice yield in the coastal region.

## Introduction

Apart from climate induced sea level rise, the coastal delta of Bangladesh has become vulnerable to upstream withdrawal of water and sediment from the Ganges-Brahmaputra-Meghna basins and land subsidence.[1, 2, 3, 4] These changes might result in an increase in flooding, salinization of water resources and soil, land loss due to erosion, and degradation of the quality of ecosystem services such as crop production. It has now become imperative to assess how these imminent changes might affect the crop production, and crop production models can be effectively used for such future simulation. The Food and Agriculture Organization (FAO) released a crop growth and yield simulation model in 2009, called AquaCrop targeting at extension service providers, consultants, water managers and policy makers.[5, 6] The model is relatively easy to use and the 33 types of required input data related to climate, soil, agricultural techniques and crop characteristics can be readily derived from an experimental research. Since its release, the model has been parameterized and tested on a number of crops including maize in USA,[7, 8] Spain,[8] India[9] and Serbia,[10] wheat in Iran[11, 12] and Canada,[13] sunflower in Serbia,[10] barley in Ethiopia,[14] cotton in Syria,[15] sugar beet in Serbia,[10] teff in Ethiopia,[16] and quinoa in Bolivia.[17] These studies demonstrated that the model was able to simulate the biomass development and grain yields of these crops with reasonable accuracy.

Though the model has been tested for a number of crops in a number of diverse climatic and agro-ecological settings, its application to rice, which is a staple food providing basic nutrition for more than half of the world's population, has been very limited. The few studies that have been made on rice using AquaCrop in China,[18] India,[19] Tanzania,[20] western Africa[21] and southeast Asia[22] either did not report many important model parameters or did not properly parameterize the model. Furthermore, no study has so far been made on any crop to test the performance of its salinity module. This study was conducted to evaluate the performance of the AquaCrop model to simulate the yield of dry season rice irrigated with different levels of saline water in Bangladesh.

Rice is the most important staple food crop in Bangladesh, as elsewhere in south and southeast Asia. Rice covers about 77.1% of the total cropped area of 15.0 million hectares (Mha) and 79.9% of the total irrigated area of 6.8 Mha in the country.[23, 24] The annual demand for clean rice presently stands at about 28.8

million tons (Mt).[25] This demand of rice arises from the country's total population of 150 million, which is increasing at a rate of 1.4% per annum.[26] To feed this ever arching population, the cereal demand of the country is increasing at a rate of 0.3 Mt per annum.[27] However, the land available for agriculture is decreasing at a rate of 1% per annum.[28]

More than 30% of the cultivable land in Bangladesh is in the coastal and off-shore areas, of which about 37% is affected by varying degrees of salinity. Spatial extent of saline area is increasing over time due to reduction in freshwater inflow into the rivers from upstream, introduction of brackish water for shrimp cultivation, increase in high tidal water level, etc.[2, 29] The salt affected area in the country has increased by about 27% between 1973 and 2009.[29] Sea level rise, increase in temperature and more erratic patterns of rainfall due to climate change are expected to further aggravate the salinity situation. It is thus necessary to assess the effects of soil and water salinity on food security, in particular on rice security, of the country. The AquaCrop model with salinity module can be useful in those purposes. It is to be noted that saline or salt affected soils are common in coastal areas in tropical, arid and semi-arid regions. In south Asia alone, some 9-12 Mha of lowland rice area is affected by salinity.

## AquaCrop model

AquaCrop is a canopy-level and engineering type of crop model, mainly focused on simulating the attainable crop biomass and harvestable yield in response to the water available.[5] It has achieved significant improvement in accuracy over the approach of Doorenbos and Kassam[30] while maintaining adequate simplicity and robustness. It avoids the confounding effect of the non-productive consumptive use of water on yield by separating the evapotranspiration (ET) into crop transpiration (T) and soil evaporation (E). Moreover, in AquaCrop, the functional relationship among different variables is implemented at a daily time scale, which is closer to the time scale of crop responses to water deficits.[5] In AquaCrop, soil, crop and atmosphere is considered as a continuum by including the soil with its water balance, the plant with its growth, development and yield processes, and the atmosphere with its thermal regime, rainfall, evaporative demand and carbon dioxide ($CO_2$) concentration. Additionally, some management aspects, such as irrigation and soil fertility, which affect crop development, water productivity and crop adjustments to stresses, and therefore final yield, are explicit in the model. The details of the model can be found in Steduto et al.[5] and Raes et al.[6]

For each day of the simulation period, AquaCrop requires minimum and maximum air temperatures, reference crop evapotranspiration ($ET_0$) and rainfall. Temperature data are used to calculate growing degree day (GDD), which determines crop development and phenology. $ET_0$ is a measure of evaporative demand of the atmosphere. Atmospheric $CO_2$ concentration, which influences canopy expansion and crop water productivity, is also needed. Physical characteristics of the root zone soil, including saturated hydraulic conductivity, field capacity and permanent wilting point, are required in determining root system development and water budgeting.

Canopy expansion and cover, which are determinants of crop transpiration, are simulated from the initial and maximum canopy covers ($CC_0$ and $CC_x$, respectively) using two canopy growth equations. Canopy cover during its declining phase is simulated from the $CC_x$ and starting time of canopy senescence using an exponential decay equation. A canopy growth coefficient (CGC), which is a conservative parameter, is used in the growth equations and a canopy decline coefficient (CDC), which is also conservative at least to a certain extent, in the decay equation. The green canopy cover is also adjusted for micro-advective effects (CC*).[6]

Crop transpiration in AquaCrop is calculated from the adjusted green canopy cover (CC*) and $ET_0$. The reduction in transpiration due to canopy ageing between the occurrences of maximum canopy cover and canopy senescence is taken into consideration with an ageing coefficient ( $f_{age}$ ). The more marked reduction in transpiration since the occurrence of canopy senescence is further taken into consideration with another coefficient ( $f_{sen}$ ).

The water productivity normalized for $ET_0$ and $CO_2$ concentration (WP*) and the reference harvest index ($HI_0$) are required to simulate the biomass and yield of a crop.

A deficit in root zone water content slows canopy expansion rate, reduces stomatal conductance and triggers early canopy senescence.[31] These effects are assessed in AquaCrop through three convex shaped water stress-response curves ( $K_s$ curves). Water deficit in the root zone may also provoke stomatal closure, which results in a drop in crop transpiration.[6] Such drop in transpiration is simulated by multiplying the crop transpiration when well watered with a stress coefficient for stomatal closure ( $K_{S_{sto}}$ ). Water stress, depending on its timing and severity and determinancy of a crop, may enhance or reduce harvest index (HI), which is used to obtain crop yield from final biomass. In AquaCrop, HI is adjusted in four ways for the more common stress levels, plus another adjustment for pollination failure.[5] The first four adjustments are for inhibition of leaf growth, for inhibition of stomata, for reduction in green canopy duration due to accelerated senescence, and for effect of pre-anthesis stress related to reduction in biomass. Pollination failure occurs due to severe water stress, cold or high temperature, and is quantified as a fraction of the total number of flowers that fail to pollinate.

Soil fertility affects WP*, CGC, $CC_x$ and canopy senescence of a crop. AquaCrop offers a semi-quantitative option to assess the effects of the fertility regime on these parameters and hence on the biomass and yield response. Like fertility, soil salinity also affects CGC, $CC_x$ and canopy senescence, and these parameters indirectly affect crop transpiration, WP* and biomass production. In addition, it affects transpiration directly by inducing stomatal closure. In AquaCrop, the effect of soil salinity on biomass production is described with a salinity stress–crop response curve. The curve has a lower and an upper salinity limit and its shape can be linear, convex or logistic. The effect of soil salinity is maximum (full effect) at the upper threshold of salinity and minimum (no effect) at the lower threshold. The average electrical conductivity of the saturated soil-paste extract from the root zone is the indicator of the soil salinity stress. AquaCrop simulates the movement and retention of salts in soils by using a computer routine called BUDGET[32, 33] which takes into account both convection and diffusion processes of solute transports. The routine takes water salinity as input and computes soil salinity as saturated paste extract. For that, soil salinity at the beginning of a crop season in terms of saturated paste extract is required to simulate the salinity effect. The water salinity for each irrigation is also to be specified in the irrigation file of AquaCrop along with the irrigation methods, and the timing and depths of the irrigations. The use of field bunds allows retention of water on the soil surface and controls surface runoff and infiltration and can be specified in the field management file.

## Materials and methods

For calibration and validation of the AquaCrop model, a field experiment was conducted with the boro rice of variety BRRI Dhan28 at the Bangladesh Agricultural Research Institute (BARI) farm in Gazipur (Figure 1). Gazipur is located about 55 km north to Dhaka, the capital of Bangladesh, and has an elevation of about 8 m above mean sea level. The area has a sub-tropical monsoonal climate. Three types of rice (boro, aus and aman) are cultivated in three different seasons in Bangladesh. Boro rice is cultivated with full irrigation during the months of December to May in the dry season and presently covers about 56% of total rice production.[23] BRRI Dhan28 is the most popular boro rice variety in Bangladesh. It is an early maturing, short duration, high yielding variety with a life cycle of 140 days from sowing to harvesting and an average yield of 5.0-6.0 t/ha in farmers' fields.[34] It is a salinity sensitive variety with a salt tolerance level of about 4 dS/m.

The rice seedlings of 41 days old were transplanted on 24 January, 2013 and harvested on 5 May, 2013. Five levels of irrigation water salinity with three replicates for each level were allocated to fifteen experimental plots laid in a randomized complete block design. Thus, there were three blocks with each block containing five treatments. The size of each plot was 2m×3.5 m. The treatments are described in Table 1. The first treatment ($T_1$) was the irrigation of the rice crop with a water salinity of 3 dS/m throughout the growing season. The second, third and fourth treatments ($T_2$, $T_3$ and $T_4$, respectively) were with the irrigation water salinity of 6, 9 and 12 dS/m, respectively. The fifth treatment ($T_5$) was with the increasing irrigation water salinity from transplanting to near maturity (3 dS/m up to 25 days after transplanting (DAT), 6 dS/m during 26-50 DAT, 9 dS/m during 51-75 DAT and 12 dS/m during the rest of the growing period).

The salinity in irrigation water was created with a 2:1 mixture of sodium and calcium chlorides. Five overhead reservoirs were installed to provide saline water irrigation to the five types of experimental plots. The irrigation water salinity was measured by an auto-recording electrical conductivity meter. The soil salinity at the beginning of a crop season was obtained from vacuum extracted water of manually saturated soil from the root zone following national guidelines.[35] About 1120 mm of irrigation was provided with a total of 90 irrigations to each experimental plot. In addition, about 200 mm of irrigation water was applied during the land preparation. Thus, there was no shortage of irrigation water supplied to the experimental plots. There were also four rainfall events with a total rainfall of 43 mm during the growing period.

**Table 1** Brief description of the different saline water irrigation treatments used in this study

| Treatment | Description | Role in model |
|---|---|---|
| $T_1$ | Irrigation with water salinity of 3 dS/m | Reference condition |
| $T_2$ | Irrigation with water salinity of 6 dS/m | Model calibration |
| $T_3$ | Irrigation with water salinity of 9 dS/m | Model validation |
| $T_4$ | Irrigation with water salinity of 12 dS/m | Model validation |
| $T_5$ | Irrigation with water salinity of 3 dS/m up to 25 DAT, 6 dS/m during 26-50 DAT, 9 dS/m during 51-75 DAT and 12 dS/m afterwards | Model validation |
| $F_1$ | Irrigation with saline water at farmer's field | Model validation |

The soil of the BARI farm was analyzed for its texture and fertility. The soil texture was silty loam and the estimated fertilizer doses were 245, 90, 120 and 83 kg/ha for urea, triple super phosphate, muriate of potash and gypsum, respectively. Urea was applied in three equal splits during the land preparation, 30 DAT and 60 DAT. The other fertilizers were applied during the final land preparation. In addition, intercultural operations were done and pesticides were applied when required.

Physiological and yield contributing characters of rice, such as days to maximum canopy cover, flowering, senescence, maximum rooting depth, grain formation and maturity, duration of flowering, rooting depth, etc., were recorded for each plot. Green leaf area was measured with a leaf area meter, and dividing the leaf area by the corresponding ground surface area, a leaf area index was obtained. Such index was obtained for three growth stages: vegetative, booting and grain formation. Canopy cover was estimated from the leaf area index using an empirical relation between the two variables.[18, 36] Above ground biomass was measured from the crop cut at harvest and drying the biomass at 60 °C for 48 h in an oven.

In parallel to the above experiments, a field monitoring program was carried out in the same season in Satkhira district of southwest coastal region to gather data and information required in AquaCrop as per local farmers' practices (referred to as farmer's field '$F_1$' in Table 1). The farmer transplanted the same variety of rice on 8 February, 2013 and harvested on 8 May, 2013. He provided different fertilizers according to the local practice, and the doses were adequate for the crop as per fertilizer recommendation for the area.[37] A total of 17 irrigations were applied to the field with the irrigation water salinity varying between 1.8 and 4.1 dS/m. There was 78 mm of rainfall in Satkhira during the growing period of rice.

Daily climatic data, such as maximum and minimum temperature, sunshine hour, relative humidity, wind speed and rainfall, during the crop season were collected from a nearby weather station of the Bangladesh Rice Research Institute (BRRI) at Gazipur. These data for Satkhira were collected from the local office of the Bangladesh Meteorological Department (BMD). $ET_0$ was calculated for both locations following the FAO Penman-Monteith method[38] with the $ET_0$ calculator. The daily $ET_0$ values for the growing season are given in Figure 2. The $ET_0$ values were found to vary between 1 and 6 mm/day at Gazipur and between 1 and 7 mm/day at Satkhira. The values at Satkhira were higher than that of Gazipur.

The calibration process of the AquaCrop model is described in detailed in the AquaCrop Reference Manual.[33] In brief, it requires observed green canopy cover and biomass production in two fields: one with and the other without salinity stress. Both fields are to be well watered and fertilised to avoid water and fertility stresses, respectively, on crop development and production. Thus, the calibration actually consists of linking an observed reduction in total above ground biomass in a stressed field with the salinity stress in that field. The total salinity stress is the combined effects of four different types of stresses linked to canopy expansion, maximum canopy cover, canopy decline and stomatal closure. During calibration, AquaCrop evaluates these individual stresses and combine them to yield the canopy cover, transpiration and biomass production in the stressed field. The user can fine tune the individual stress coefficients to improve the calibration result. Once calibrated, a stress-response curve can be used to obtain the stress coefficient corresponding to a level of soil salinity stress.

## Results and discussion

The strategy followed in calibration and validation of the AquaCrop model with saline water irrigation was to calibrate the model with the second treatment ($T_2$) and to validate it with the third ($T_3$), fourth ($T_4$) and fifth ($T_5$) treatments while keeping the first treatment ($T_1$) as the reference treatment in all the four cases. This provided a rigorous testing of the applicability of the selected model parameters under diverse salinity regimes. The model was calibrated against three canopy cover estimates, one grain yield and one biomass production. The input parameters, including the phenological observations, used in the model are provided in Table 2. Most of the parameters used in the model are according to the suggested values in the AquaCrop Reference Manual.[32] The canopy decline coefficient was found to be 0.5%/GDD and the canopy growth coefficient to be 0.8%/GDD, both of which were at the higher sides of the suggested values. However, slightly smaller values for both the lower and upper salinity thresholds (2 and 10 dS/m, respectively) than that suggested in the AquaCrop Manual (3 and 11.3 dS/m) provided a better simulation of the observed rice yield, biomass and canopy cover. The shape of the salinity stress coefficient curve was found to be convex with a shape factor of 2.4 (Figure 3). A plot (not shown here) of the observed grain yield (or biomass) against irrigation water salinity in the first four treatments ($T_1$-$T_4$) indicated that the shape of the salinity stress coefficient curve would be convex. Also, other shapes and shape factors were tried, but the above curve produced a better calibration.

**Table 2** Input values used in the AquaCrop model for calibration under saline water irrigation regime (the second saline water irrigation treatment)

| Parameter with unit | Value used |
|---|---|
| $CC_0$ (%) | 3 |
| $CC_x$ (%) | 95 |
| Canopy decline (days) | 35 |
| Time to recover (DAT) | 7 |
| Time to maximum canopy (DAT) | 64 |
| Time to senescence (DAT) | 72 |
| Time to maturity (DAT) | 98 |
| Time to flowering (DAT) | 68 |
| Duration of flowering (days) | 7 |
| Length building up HI (days) | 30 |
| Determinancy linked with flowering | yes |
| Maximum effective rooting depth (cm) | 38 |
| Time to maximum rooting depth (DAT) | 72 |
| Minimum effective rooting depth (m) | 0.3 |
| Shape factor describing root zone expansion | 2 |
| Base temperature for GDD (°C) | 8 |
| Upper temperature for GDD (°C) | 30 |
| Crop coefficient for transpiration at CC = 100% | 1.10 |
| Decline in crop coefficient after reaching $CC_x$ (%/day) | 0.15 |
| Effect of canopy cover in reducing soil evaporation in late season (%) | 50 |
| $WP^*$ (gm/m$^2$) | 19 |
| Reference harvest index (%) | 50 |
| Leaf growth threshold ($p_{exp,\ upper}$) | 0.00 |
| Leaf growth threshold ($p_{exp,\ lower}$) | 0.40 |
| Shape factor for leaf growth stress coefficient curve | 3 |
| Stomatal conductance threshold ($p_{sto}$) | 0.50 |
| Shape factor for stomata stress coefficient curve | 3 |
| Senescence stress coefficient threshold ($p_{sen}$) | 0.55 |
| Shape factor for senescence stress coefficient curve | 3 |
| Soil water depletion threshold for failure of pollination ($p_{pol}$) | 0.75 |
| Possible increase in HI due to water stress before flowering (%) | 0 |
| Excess of potential fruits (%) | 200 |
| Coefficient, inhibition of vegetative growth on HI | 10 |
| Coefficient, inhibition of stomata on HI | 5 |
| Allowable maximum increase of specified HI (%) | 15 |
| Cold stress temperature for pollination (°C) | 8 |
| Heat stress temperature for pollination (°C) | 35 |
| Salinity stress, lower threshold, $ECe_n$ (dS/m) | 2 |
| Salinity stress, upper threshold, $ECe_x$ (dS/m) | 10 |
| Shape factor for salinity stress coefficient curve | 2.4 |

The field-estimated canopy covers in the second treatment ($T_2$) were 37%, 71% and 64% at the vegetative, booting and grain formation growth stages, respectively, whereas the simulated canopy covers were 40%, 72% and 57%, respectively, for the same treatment. The model calibrated grain yield was 5.52 t/ha as against an average observed grain yield of 5.49 t/ha in the second treatment. The calibrated biomass was 11.48 t/ha and the observed biomass was 11.19 t/ha. The model results also indicated that the potential biomass yield in absence of salinity stress would be about 13.54 t/ha.

The calibrated effects of soil salinity stress on different stress coefficients indicated that an increase in irrigation water salinity to 6 dS/m in the second treatment ($T_2$) from 3 dS/m in the first treatment ($T_1$) resulted in a decrease in maximum canopy cover of 6%, reduction in CGC of 1%, stomatal closure of 1% and a decline in average canopy cover of 0.53% per day. The combined effect of the four stresses was a reduction in biomass production of 15%. The calibrated soil salinity stress–biomass curve is shown in Figure 4. A soil salinity stress of 100% in the figure indicates the salinity condition at which crop production is no longer possible and a zero stress indicates the condition at which biomass production is not affected by soil salinity.[33] The dots are generated by the model once it is calibrated.

The calibrated parameters were then used to validate the model with the third ($T_3$) to fifth ($T_5$) treatments. During validation, irrigation water quality and initial soil salinity were changed according to the measured values under the three treatments. $CC_x$, time to senescence, length building up HI and $HI_0$ were provided for optimal conditions as suggested in Raes et al.[33] Other phenological parameters, such as time to maximum canopy, time to flowering, duration of flowering, maximum rooting depth, time to maximum rooting depth and canopy decline, were provided as observed in the field experiments. There were no significant differences in values of these parameters among the treatments except for the time to maximum canopy and the maximum rooting depth in the fourth treatment ($T_4$). The time to maximum canopy was found to be 11% higher and the maximum rooting depth to be 36% lower in $T_4$ compared to $T_1$.

The simulated rice yields and final biomasses for different treatments are plotted along with their corresponding observed values in Figures 5 and 6, respectively. The model simulated the actual yields and biomasses of the boro rice grown under different saline water regimes quite well. For grain yield, the mean absolute error calculated from the experimental data was only 0.12 t/ha and the root mean square error was only 0.03 t/ha. For biomass, these values were 0.43 t/ha and 0.22 t/ha, respectively, and for canopy cover 10% and 8%, respectively.

Since the first treatment ($T_1$) was used in model calibration as the reference treatment indicating no water, salinity and fertility stresses to the crop, the yield obtained from the model without these stresses would indicate the potential yield for this particular variety under the given climatic and field conditions. The simulated rice yield thus obtained under the first treatment was 6.52 t/ha, which was very close to the observed yield of 6.49 t/ha. The simulated biomass at harvest was 13.55 t/ha and the observed biomass was 13.03 t/ha.

The model results also indicated a soil salinity stress of only 3% in an average crop cycle in this treatment. The effect of salinity was a reduction in yield of 0.49% and in biomass of 0.49%. During the period from 24 January to 1 May, 2013, total $ET_0$, rainfall, irrigation and growing degree-days were 316 mm, 53 mm, 1080 mm and 1341 °C-day, respectively. Simulated evaporation and crop transpiration were 91 mm and 236 mm, respectively, and the drainage volume from the root zone was 876 mm. The water productivity was found to be 1.98 kg of rice grain per cubic meter of water evapotranspired.

Since the irrigation water salinity in the treatment $T_1$ was around 3 dS/m, which is slightly higher than the lower threshold of 2 dS/m used in the model calibration and validation discussed earlier in this section, the model was rerun for this treatment considering the salinity stress. The simulated yield during this time was found to be 6.48 t/ha and the biomass to be 13.49 t/ha.

The applicability of the model was further tested in a different agro-ecological setting at Satkhira in southwest coastal Bangladesh. The same variety of rice (BRRI Dhan28) was cultivated by a farmer in his own field (referred to as '$F_1$' in Figures 5 and 6) following the local practice and input uses. The planting date of 44 days old seedling was 8 February, 2013 and the harvesting date was 8 May, 2013. The field was monitored throughout the growing period, and the required data for the AquaCrop model were gathered. The model was then run keeping its parameters the same as the calibration and validation runs with the experimental data in Gazipur in central Bangladesh. The yield obtained by the farmer was 5.90 t/ha and that simulated by the model was 5.79 t/ha. These results further indicate that the calibrated AquaCrop model captures the yield variation of the boro rice reasonably well.

The salinity module of the AquaCrop model (version 4.0) was released in June 2012 to simulate crop growth and yield under a saline environment. Given that about 955 Mha of land in the world fall under different categories of salt affected soils, and the groundwater and irrigation water in many places are saline, the module may find its potential application in those environments. An early application of the module through this study will be useful to its future users. Our experience shows that the module can be applied in diverse environmental and climatic settings if properly calibrated. The model performance was relatively better for grain yield and biomass production than for canopy cover. This could be due to the fact that canopy cover was not directly measured. To achieve a good calibration, the model parameters needed fine tuning around their suggested values in the AquaCrop Reference Manual and the values that we obtained through the carefully designed field experiment and monitoring system. The same calibration parameters on lower and upper salinity thresholds, stress-response curve shape and shape factor, observed reduction in biomass and maximum canopy cover in the stressed field, etc., were used in all the validation runs. This provides a strong basis for using the model in different saline and climatic conditions. The calibrated model is now being used to assess the vulnerability of the rice crop to changes in soil and water salinity and climatic parameters due to global warming induced climate change in coastal Bangladesh.

## Conclusions

The AquaCrop model was parameterized and tested for boro rice under different saline soil and irrigation conditions in Bangladesh. A field experiment was conducted in central Bangladesh and a field monitoring was carried out in southwest coastal region of the country in the year of 2013 to gather required input data and information for the model. The results indicated that the model captured the grain yield variation of BRRI Dhan28 with salinity variation reasonably well. The crop response versus soil salinity stress curve was found to be convex in shape with a lower threshold of 2 dS/m, an upper threshold of 10 dS/m and a shape factor of 2.4. As salinity accumulation due to climate change and upstream withdrawal is a key issue affecting crop production in Bangladesh, the model provides a tool to estimate the impacts of future changes in water and soil salinity as well as climatic parameters on rice yield.

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## Notes and references

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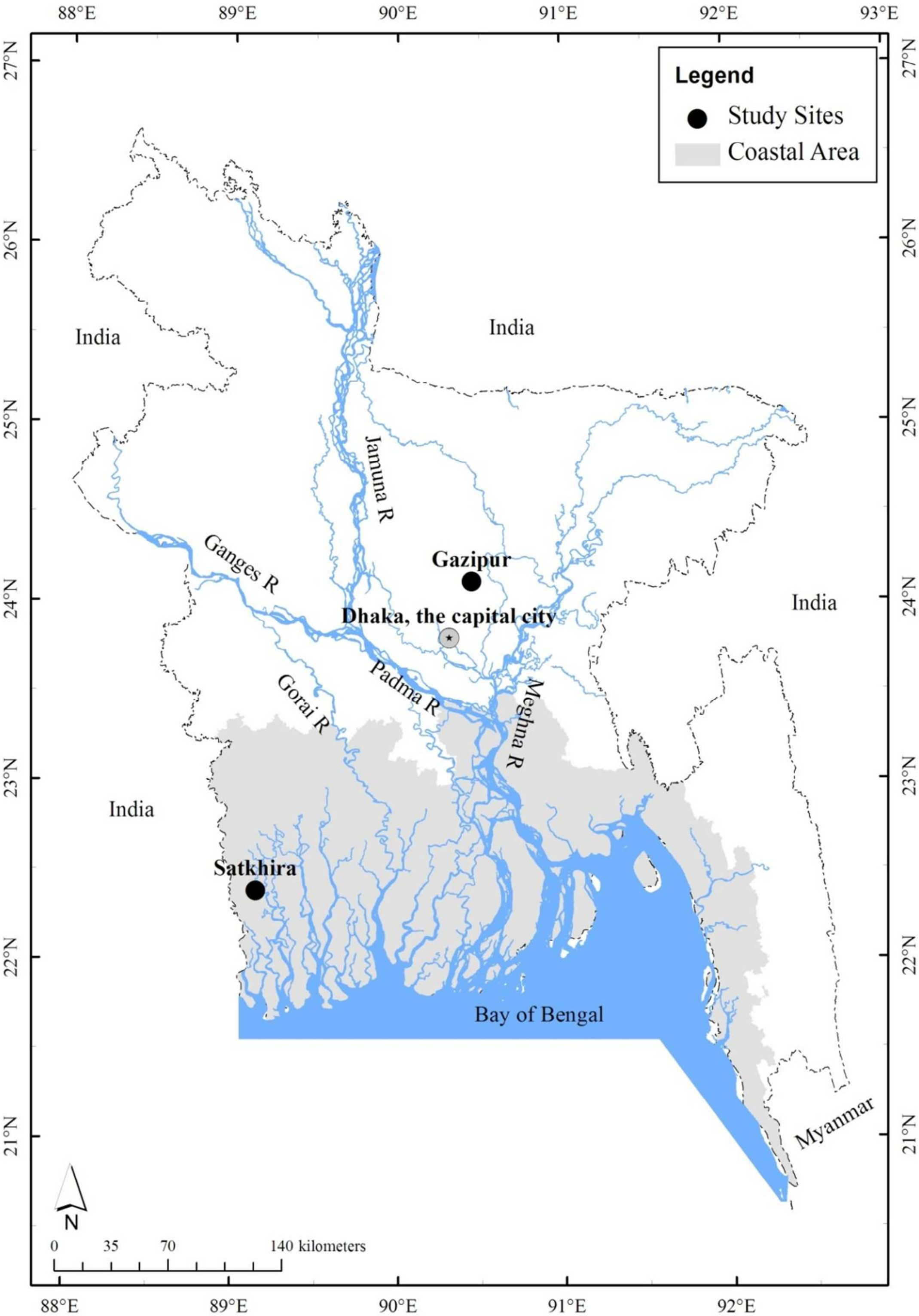

**Fig. 1** Locations of the experimental and field sites in Bangladesh.

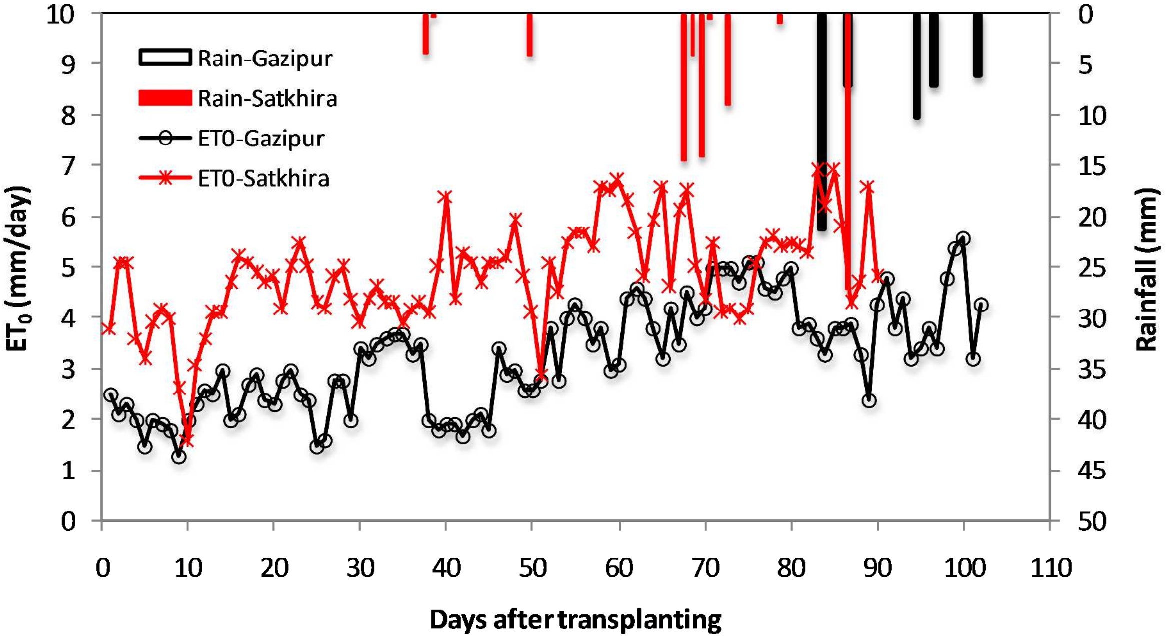

**Fig. 2** Variation of daily $ET_0$ values and occurrences of rainfalls at Gazipur and Satkhira during the boro rice growing period.

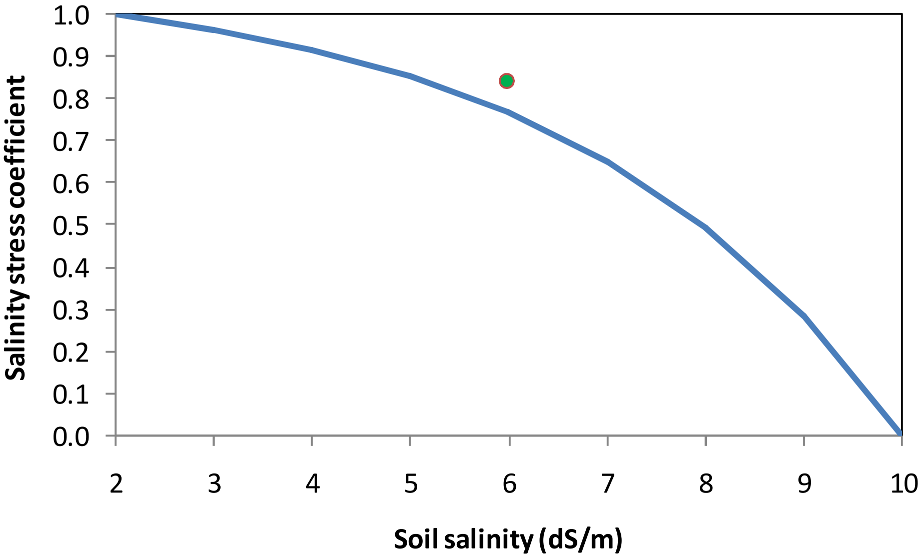

**Fig. 3** Soil salinity stress ($Ks_{salt}$) curve used in model calibration for BRRI Dhan28 (Note: the dot indicates the ratio of observed biomasses at stressed ($T_2$) and reference ($T_1$) fields used also in the calibration).

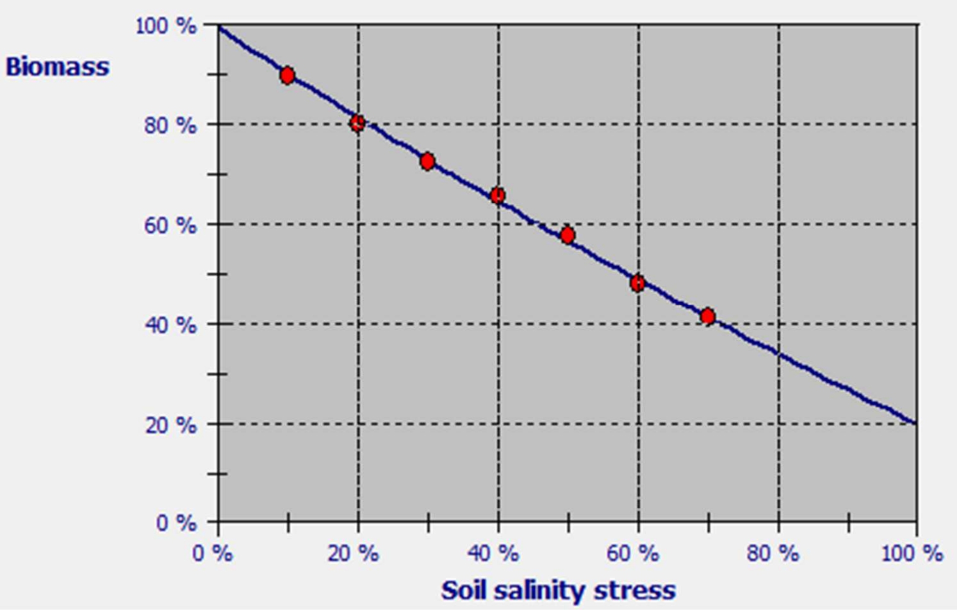

**Fig. 4** Calibrated soil salinity stress – biomass curve for BRRI Dhan28.

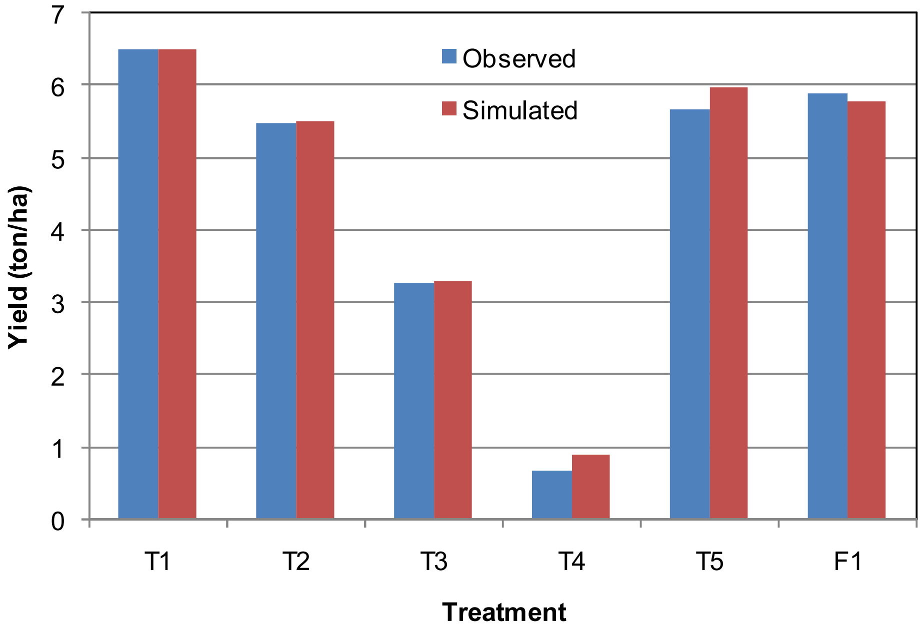

**Fig. 5** Observed and simulated rice yields under different saline water regimes in Gazipur and Satkhira.

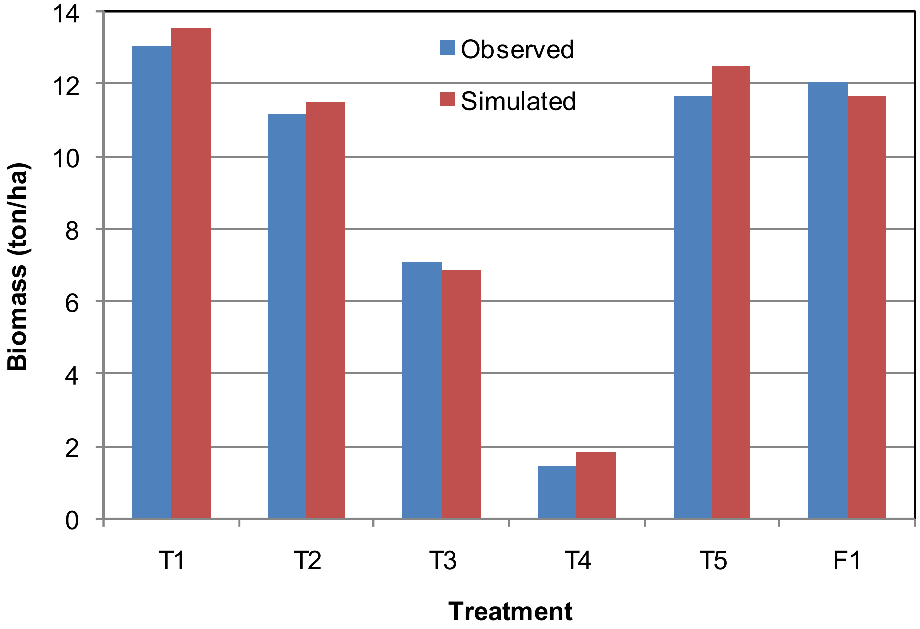

**Fig. 6** Observed and simulated rice biomasses under different saline water regimes in Gazipur and Satkhira.