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Application of AquaCrop model in deficit irrigation management of cabbages in Keiyo Highlands

Kiptum C. K*[1], Kipkorir E. C[2], Munyao T. M[1] and J. M. Ndambuki[3]

[1]Department of Earth Sciences, University of Eldoret, P. O. Box 1125 Eldoret, Kenya.
[2]Department of Civil Engineering, University of Eldoret, P. O. Box 1125 Eldoret, Kenya.
[3]Department of Civil Engineering, Tshwane University of Technology, Private Bag Pretoria, South Africa.

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Crop growth can be simulated under different water application using simulation models. The main purpose of deficit irrigation is high water productivity with less application of water to plants. In this research, the potential of AquaCrop to simulate the growth of cabbages in Keiyo Highlands (0°22'45''N and 35°32'9", 2586 m.a.s.l) under nine different irrigation treatments in the dry season between December to February was studied. Statistical comparisons of observed and simulated biomass showed that R^2 = 0.96, Root mean square error (RMSE) = 0.38 tons and coefficient of residuals = -0.17. The results showed that the model overestimated the biomass of cabbages. The model also provided excellent simulation of canopy and yield. In this study water productivity of 17 g/cm^2 and Harvest index of 76% were found for cabbages.

Key words: Deficit irrigation, AquaCrop, cabbage 'Riana' and water productivity.

INTRODUCTION

Cabbage growing done all over Kenya is mainly for domestic market. The major production counties where yields are 25 tons/hectare are Narok, Molo, Nakuru and Kericho among other cool climate areas (HCDA, 2008). One such other area is Keiyo Highlands where cabbages are grown for food and source of income (SARDEP, 2001). With adequate soil moisture, cabbages can be planted throughout the year. However, such soil moisture conditions are not available during the dry season.

Cabbage grown in the dry season gives much profit particularly in areas where water application is by drip irrigation (Ojo et al., 2009). A study by Wambani et al. (2007) observed that during the dry season in Kaisagat village near Kitale town in North-western Kenya, people grew vegetables along the river valleys. In Keiyo Highlands, people normally practice irrigation using sprinkler, hand/ bucket and drip irrigation. Therefore there is need for farmers to know the amount of water needed during the dry season to be able to take advantage of good prices in the dry season and also take advantage of using less nitrogen fertilizer when irrigating cabbages as was observed in maize (Sanavy et al., 2009). In addition, farmers should be encouraged to plant drought resistant varieties of cabbage during the dry season like 'Riana' and 'Pruktor' (Wambani et al., 2007).

Many crop-growth models, based on physiological processes, have been developed and applied in water management projects with varying degrees of success. Many of these models however, have not yet been tested under deficit irrigation in the dry seasons of Keiyo Highlands. For example, CROPWAT model cannot be used for crop simulation because it has the problem of simulating evapotranspiration and therefore, the crop yield reductions estimate by this model should be taken with caution (Cavero et al., 2000). In addition such models demand advanced skills for their calibration and operation and need a large number of parameters (Steduto et al., 2009). To address these concerns and in

*Corresponding author. E-mail: chelalclement@yahoo.com.

trying to achieve an optimum balance between accuracy, simplicity and robustness, a new crop simulation model named AquaCrop has been developed by FAO (Steduto et al., 2009).

To date, no study on simulation of the effects of deficit irrigation on cabbage with AquaCrop has been reported in literature. Therefore, some previous studies that have applied AquaCrop for other Crops are presented as follows. Farahani et al. (2009) and Garcia-Vila et al. (2009) investigated AquaCrop model for cotton under full and deficit irrigation regimes in Syria and Spain. Mhiza, (2010) studied AquaCrop on maize in Zimbabwe while Salemi et al. (2011) used AquaCrop on winter wheat in Iran. They showed that the key parameters such as normalized water productivity, canopy cover and total biomass, for calibration must be tested under different climate, soil, cultivars, irrigation methods and field management. In addition the researchers found out that AquaCrop model is a new model for scenario analysis that provides a good balance between robustness and output precision. Modern analysis of irrigation methods place emphasis on getting more yield from each drop of water used.

The main objective of the study was to test the ability of AquaCrop model, to simulate cabbage growth under full and deficit irrigation in Chepkorio in the Highlands of Keiyo.

MATERIALS AND METHODS

Study area

Data were obtained from a sheltered from rain irrigation field trial experiments done at Chepkorio farm in Keiyo District (0° 22' 45" N, 35° 32' 9"E, 2586 masl) in Kenya. Rain shelter is normally used when doing deficit irrigation as was used by Geerts et al. (2005), when he was developing guidelines for deficit irrigation for quinoa. Chepkorio (Figure 1) is located in Keiyo South District of Keiyo Marakwet County. The average rainfall between December and February is 150 mm. The value varies between 122 mm in Kipkabus to 185 mm in Elgeyo Forest. Analysis of the record shows that high rainfall depths can occur at the start or at the end of the season but reduces to zero in the middle of the season and hence affecting the growth of cabbages during the mid season stages. To supplement the rainfall there is need for irrigation and particularly drip irrigation which results in saving of scarce water resources in the dry season.

Experimental description

A field experiment conducted in 2011/2012 dry season was chosen because it allowed crops to cope with environmental variability unlike pot plants which have artificial conditions. Therefore the field experiment is advantageous because the results can be adopted by farmers with no changes. Riana cabbage variety was chosen because of its drought resistance and high yields of 98 tons per hectare (Wambani et al., 2007). The experimental site has silty loam soil with a water holding capacity of 150 mm in a 1 m, soil profile. The moisture content for silt loam soil at field capacity and wilting point were 23 and 8% by volume respectively. The long term weather parameters were obtained from the New-FAOClim software for Kaptagat station which was near the study area. The FAO Penman-Monteith method (Allen et al., 1998) was used to calculate reference evapotranspiration (ET_o). The monthly ET_o (mm/day) of 2.5 mm, 2.8 mm and 3.5 mm were observed for December, January and February respectively. The rain gauge installed at the site to measure rainfall recorded was 37.4, 2.2 and 28.2 mm in the months of December, January and February respectively. While the average temperatures were 17.3, 17.7 and 19.0°C in December, January and February respectively.

The peak cabbage crop evapotranspiration was found to be 3.64 m/day calculated using the Equation 1 or 11 mm/3 days. By using plant spacing of 0.45 m by 0.6 m and wetting perimeter of 10% for drip irrigation (Finkel, 1982) the amount of irrigation to apply to a plant during irrigation time was 0.82 L. This amount of water ensured that the cabbage grew without water stress.

$$ET_c = K_c ET_o \quad (1)$$

Where ET_c is the cabbage crop evapotranspiration, K_c is the crop coefficient and ET_o is the reference evapotranspiration (Allen et al., 1998).

Experimental details

The experiment was conducted using field trials in a randomised complete block design (RCBD) with irrigation treatments as the subplots. The field was divided into three blocks. Each block contained nine irrigation treatments randomly distributed in each block. This meant that there were three replicates per treatment. Two rows of cabbage of six metres each represented a treatment. This type of research design was chosen because it is simple and easy to analyse using one-way analysis of variance (ANOVA). ANOVA is a technique used to test claims involving three or more means (Bluman, 2004). Treatment 1 was a control where there was no water stress during the whole growing period. Irrigation was done after three days in every growth stage. Treatment 2 received half the irrigation events of Treatment 1. Reduction of irrigation events than those of treatment 1 meant water stress. Treatments 3 had half irrigation events in the initial stage only, Treatment 4 had half irrigation events in the development stage only, Treatment 5 had half irrigation events in the mid season stage only and Treatment 6 had half irrigation events in late season only. Treatments 7, 8 and 9 had two consecutive stages of water stress. In Treatment 7, the initial and development stages were stressed, in Treatment 8, the development and mid season stages were stressed and Treatment 9, was stressed in the mid and late season stages. Irrigation was by drip where a 20 mm polyvinyl chloride (PVC) pipe delivered water from the tank into different drip lines (rows of cabbage) with emitters at each position of cabbage plant. Since the stress of cabbages was by varying the interval of irrigation, the drip lines that were to be irrigated were opened while those not to receive irrigation were closed using a gate valve installed on each branch leading from the PVC pipe. Each treatment had two drip lines with each drip line having 10 plants. The row spacing was 0.45 m and the length was 6.0 m. To apply 0.82 L of water to each a plant, duration of irrigation was one hour forty minutes. Above dry ground biomass was measured every two weeks with the first measurement done during the transplanting day, canopy cover was measured fortnightly between 12.00 and 1.00 pm local time, the yield was measured at the end of the ninety days. Maximum rooting depths were measured after 90 days by digging to a depth of 1 m around the mature cabbage to expose the roots. Yield per plot were determined by harvesting four cabbages heads selecting randomly from each plot and the average weight determined. The average weight determined was multiplied by

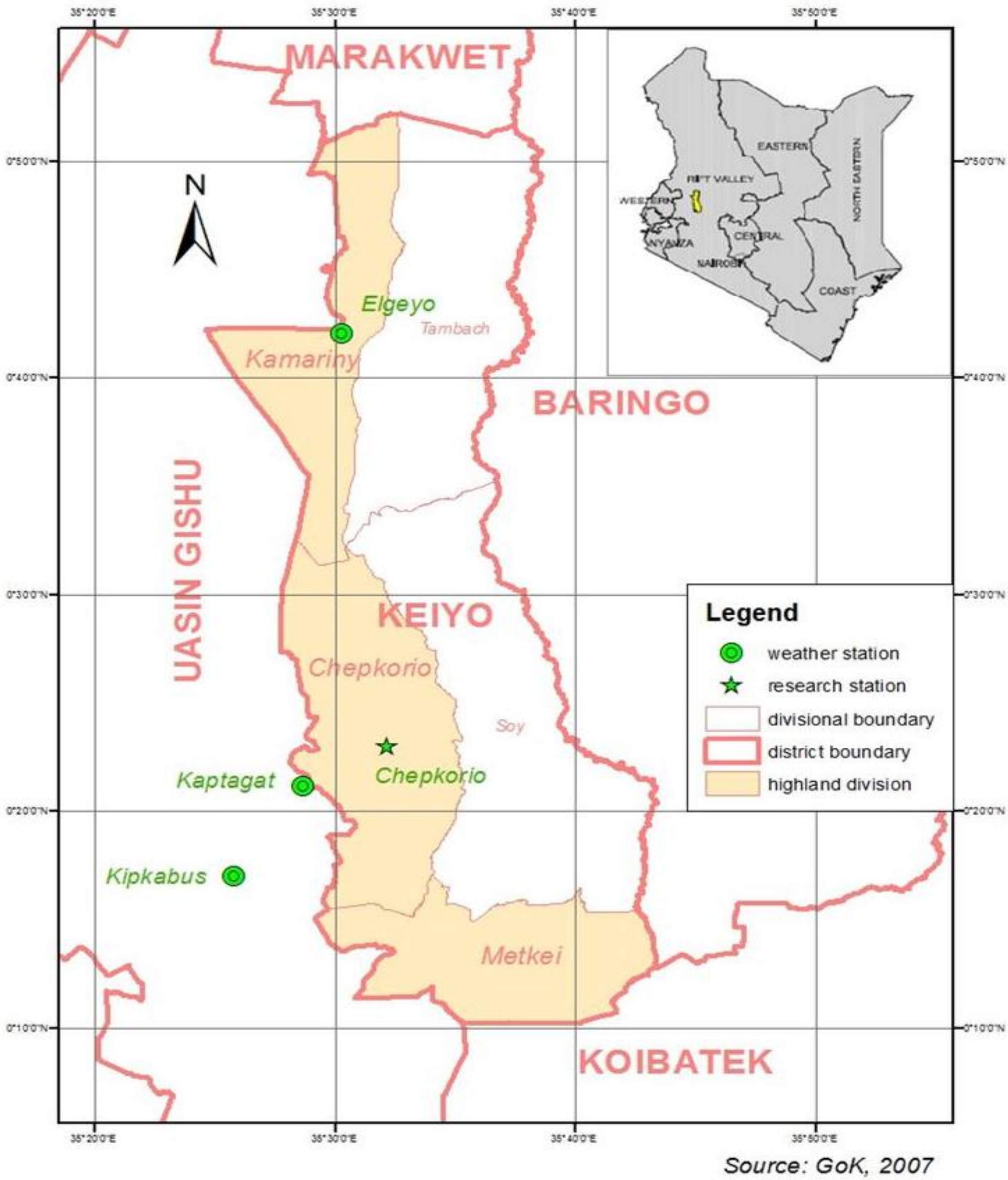

Figure 1. Study area.

37037 (plant density/ha) to get the weight of cabbages per hectare.

Cultural management

Seeds of 'Riana' cabbage variety were first planted on the seed bed before transplanting onto three blocks with nine treatments each (Table 1). The seed bed was prepared on 4th October, 2011. The seed bed measured 1m wide and 3 m long. Two ploughings and one harrowing were done to make the seedbed fine and good for planting. Three containers of Farm Yard Manure (FYM) representing 20 kg for 1 m^2 were incorporated and mixed well in the seedbed. The bed was raised to 20 cm high; ridomil fungicide was drenched in the soil prior to planting as a disease preventive

Table 1. Irrigation treatments and the number of irrigation events.

Treatment	Growth Stage/ Period in days				Description
	Initial	Development	Mid	Late	
	20	30	30	10	
Controls-Full irrigation events and half irrigation					
Treatment 1	7	10	10	3	Normal watering
Treatment 2	4	5	5	1	Half watering
One period with half irrigation events					
Treatment 3	4	10	10	3	Water stress at initial stage
Treatment 4	7	5	10	3	Water stress at dev. stage
Treatment 5	7	10	5	3	Water stress at mid season
Treatment 6	7	10	10	1	Water stress at late season
Two consecutive periods with half irrigation events					
Treatment 7	4	5	10	3	Water stress in the first two periods
Treatment 8	7	5	5	3	Water stress in dev.&midseasons
Treatment 9	7	10	5	1	Water stress in the last two periods

measure. The experimental site was wetted to attain field capacity on 30th November, 2011. All treatments received the same cultural practices of fertilizer application and control of pests, diseases and weeds. At the time of planting 120 kg/ha of single superphosphate was applied and no top dressing. Top dressing was not done because composed manure had been applied before ploughing. Weeding was only done once by using a hoe. The main pests at the growth stage were aphids which were prevented by spraying the field four times to prevent the pests from eating the leaves. The crops were harvested manually on 28th February, 2012.

Irrigation layout

A 1000 L tank was placed on platform of timber frames (100 mm by 50 mm) spaced at 160 mm centre to centre on 150 mm diameter cedar posts firmly grouted to the ground by use of concrete as shown in Figure 2. The size of tank was chosen based on the amount of water required by the plants. There were nine treatments replicated thrice each with 20 plants giving a total of 540 plants. One plant required 0.82 L (or dose 11mm) and therefore in each irrigation day 442.8 L of water were required assuming irrigation of all the plants. During each irrigation day the tank was filled to capacity to ensure minimal pressure variation throughout the irrigation time.

The pipeline was connected to the tank by use of a tank connector at 100 mm above the bottom of the tank in order not to draw mud from the bottom of the tank. A gate valve was installed at the middle of the drop pipe which was 2.5 m. The diameter of the pipeline was 20 mm.

Water was manually lifted to the tank using rope and bucket from a 15 m deep well. Irrigation was done in the evening. Irrigation started at 5.00 pm and ended at 6.40 pm local time. This was done to minimise evaporation of dripping water.

Calibration and validation

Conservative and cultivar specific parameters are shown in Table 2 - default parameters of AquaCrop vegetable (Raes et al., 2009a), used in the calibration simulations for irrigated cabbage in Keiyo Highlands. Calibration was done using results of treatment 1 and validation done using results of the remaining treatments. AquaCrop version 3.1 was used in the study.

The default model input parameters for vegetables reported by Raes et al. (2009a), were used for simulations and are shown in Table 2 for reference. Only parameters that varied with cultivar and environment were adjusted depending on availability of data about the parameters. The parameters that were specified during calibration include the following: soil parameters (soil water content at field capacity, soil water content at permanent wilting point and soil depth), maximum canopy cover, plant density, maximum rooting depth (Z_r), length of growth cycle and reference harvest index (HI_o). Cultivar specific parameter for length of the growth cycle of Riana was specified as 90 days during calibration.

Step-wise approach

The procedure started with fitting the canopy cover by adjusting the maximum cover. The second parameter that was adjusted was the harvest index so as to obtain the observed yields. Table 3 gives the summary of the variables used to compare model output and observed data (reference variables) and the parameters that were adjusted or specified from observations (degrees of freedom) during calibration.

RESULTS

Table 4 shows the results obtained in the experimental field which were used to calibrate and validate AquaCrop model. The results were used to calibrate and validate the model.

In Table 4, all the treatments started with an initial cover of 1% and attained a maximum canopy cover of 100% though at different times. Canopy decline occurred in all the other treatments in the late season stage except

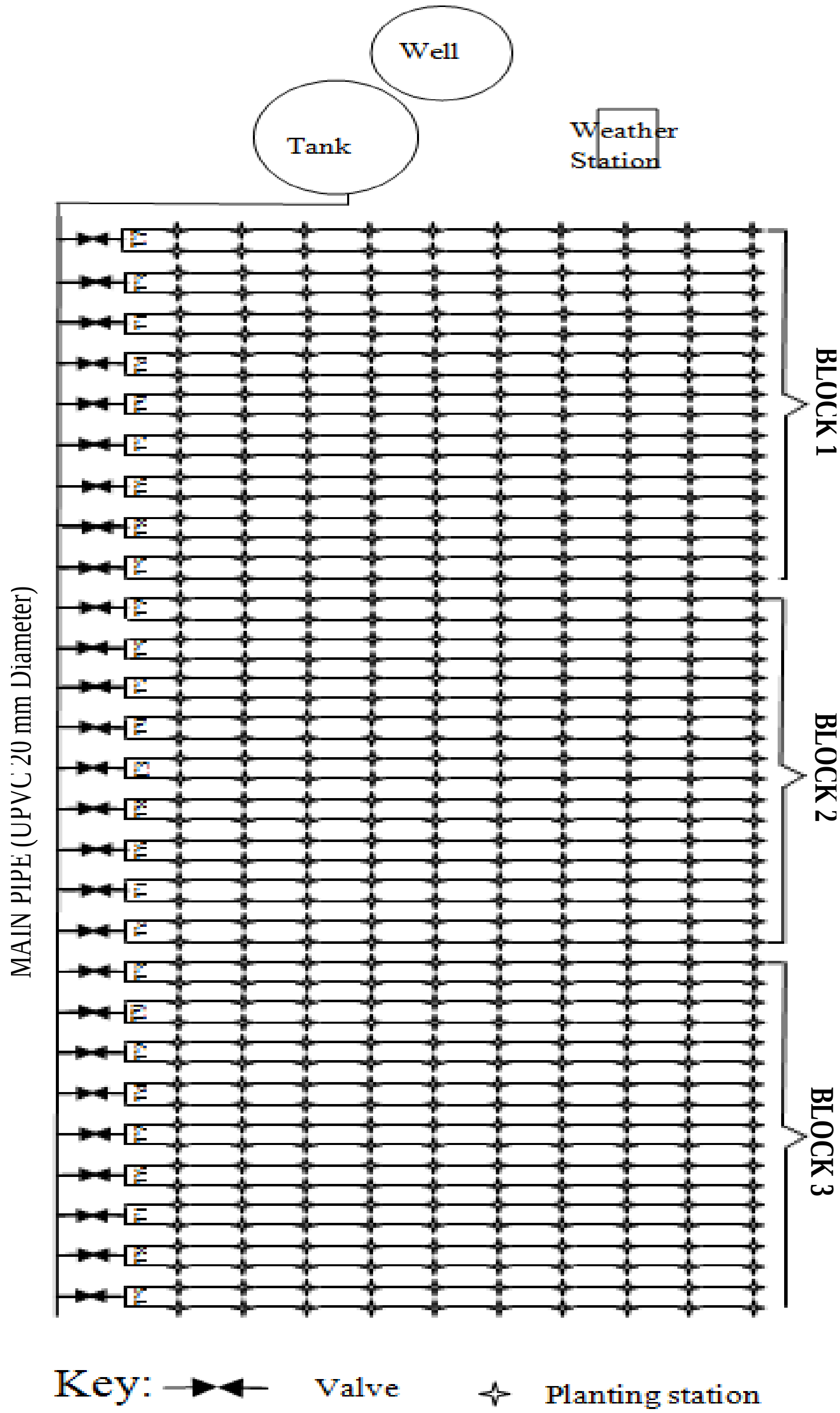

Figure 2. Irrigation layout.

treatments 1 and 6. All the treatments started with above ground dry biomass of 0.1 g and attained different masses after 90 days with the highest mass being observed in treatment 1 (334.5 ± 24.7 g). The highest yield of 94 ± 2 $Mg.ha^{-1}$ was observed in treatment 1 and the lowest in treatment 2 (67 ± 2 $Mg.ha^{-1}$). The yields from the experiment were statistically different at α = 0.05 attributed to different amounts of water used in the treatments. The yields were above 80 $Mg.ha^{-1}$ (Sarker et al., 2003) but lower than 98 $Mg.ha^{-1}$ (Wambani et al., 2007). The maximum rooting depth of 0.3 m was observed in treatment 1 which showed that the rate of

Table 2. Conservative and cultivar specific parameters.

Description	Value	Units	Comment
Conservative (generally applicable)			
Base temperature	10	°C	
Upper temperature	30	°C	
Growing cycle	140	Days	For Keiyo 90 days
CC_o	1.5	%	
Mode of planting	Sowing		For Keiyo transplanting
Cover per seedling	5.0	cm^2	
Maximum canopy cover	85	%	Depends on plant density
Plant density	37000	Plant/ha	
Canopy decline			Very slow
Day 1 to recovery	7	Days	
Day 1 to maximum canopy	70	Days	50
Senescence	120	Days	80
Harvest	140	Days	90 days for the site
Root system			Shallow for the site
Maximum effective depth			0.3
Water productivity ($WP_b^{*)}$)	17.0	g/m^2	
Reference harvest index (HI_o)	80%		

Table 3. Reference variables and degrees of freedom for calibration.

Reference variable	Degree of freedom
Canopy cover (CC)	Plant density; length of growth cycle; Maximum canopy cover; Canopy decline
Soil water content (SWC)	Water content at field capacity and wilting points, maximum rooting depth
Biomass	Biomass water productivity
Yield	Harvest Index

root deepening was 3.33 mm/day.

Canopy cover (CC) calibration

Figure 3 showed that the canopy cover of observed and simulated were the same for the first 25 days and the last 47 days. The model under-estimated canopy covers between day 25 and day 53 after transplanting. The number of days to recovery, to maximum canopy cover and canopy decline were adjusted in order to get a good match between observed and simulated green canopy cover for treatment which gave R^2 of 0.9 (Figure 4) which showed that there was a strong relationship between observed and simulated canopy cover despite the overestimation in the development stage.

Biomass calibration

When running AquaCrop after calibration of canopy, the simulated above ground biomass did not match the observed. The model overestimated the biomass on the following days 32, 46, 60 and correctly simulated above ground biomass of day 0, 18, 74 and 90 (Figure 5). This indicated that the model could simulate biomass under the conservative normalised water productivity (WP_b^*) reference of 17.0 g/m^2 and no need to change it.

The regression of simulated against observed final above ground biomass was also considered to assess the correctness of the simulations during the calibration of biomass (Figure 5 and 6). The value of R^2 = 0.96 showed a strong relationship between observed biomass and simulated biomass meaning that the model did the predictions very well.

Head yield calibration

Calibration of head yield simulation was done by assessing the goodness of fit of simulated against observed head yield. The dry head yield was observed to be 9.4 $Mg.ha^{-1}$ while the simulated yield was 9.953 $Mg.ha^{-1}$ with a harvest index of 80%. This showed that

Table 4. Field data results for each treatment at certain days after transplanting.

				Canopy in %					
Day	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**
0	1	1	1	1	1	1	1	1	1
18	9	8	6	8	7	7	7	6	6
32	38	37	43	32	37	28	35	38	44
46	94	96	91	73	74	100	85	90	83
60	100	100	100	99	99	100	100	100	95
74	100	100	100	100	100	100	99	100	100
90	100	89	90	93	85	100	98	94	94
				Above ground dry biomass per plant (g)					
Day	T1	T2	T3	T4	T5	T6	T7	T8	T9
0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
18	0.6	0.7	0.9	0.7	0.7	0.5	0.5	0.4	0.9
32	13.6	11.7	13.5	9.8	10.0	10.1	10.4	8.8	13.7
46	86.3	40.3	50.4	43.6	46.6	85.0	46.6	43.4	73.6
60	125.3	105.4	113.8	108.0	101.1	107.8	109.2	107.0	101.9
74	231.2	156.1	192.3	174.3	146.5	183.1	200.5	150.9	194.7
90	334.5	240.4	313.8	297.3	243.9	301.5	293.6	234.2	284.1
				Yield in tons per hectare					
Day	T1	T2	T3	T4	T5	T6	T7	T8	T9
90	94 ± 2	67 ± 2	90 ± 13	82 ± 1	75 ± 1	91 ± 8	87 ± 2	75 ± 2	79 ± 10
				Maximum rooting depth (cm)					
Day	T1	T2	T3	T4	T5	T6	T7	T8	T9
90	30±1	26 ± 3	27 ± 3	28 ± 3	27 ± 2	28 ± 2	26 ± 2	25 ± 4	22 ± 2
				Total applied water (mm)					
	T1	T2	T3	T4	T5	T6	T7	T8	T9
	328	164	295	273	273	306	240	218	251

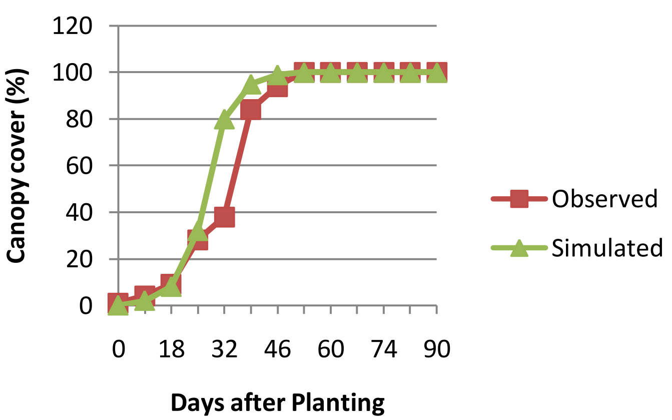

Figure 3. Observed and simulated canopy cover for treatment 1.

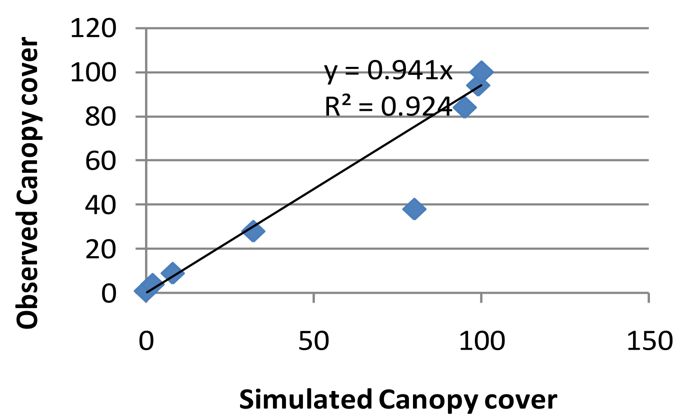

Figure 4. Observed versus simulated canopy cover regression analysis.

the model overestimated the yield and hence the need to adjust the harvest Index to 76% obtained for treatment 1.

The low Harvest Index could be due to the large wrapper leaves around the cabbage head. After adjusting the

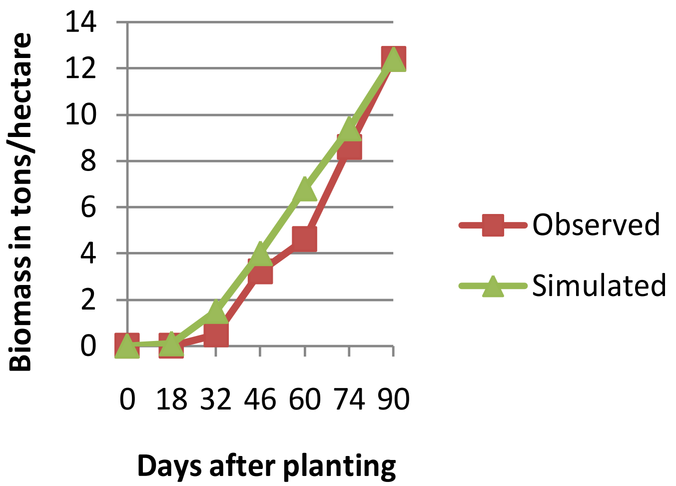

Figure 5. Observed and simulated above ground biomass for treatment 1.

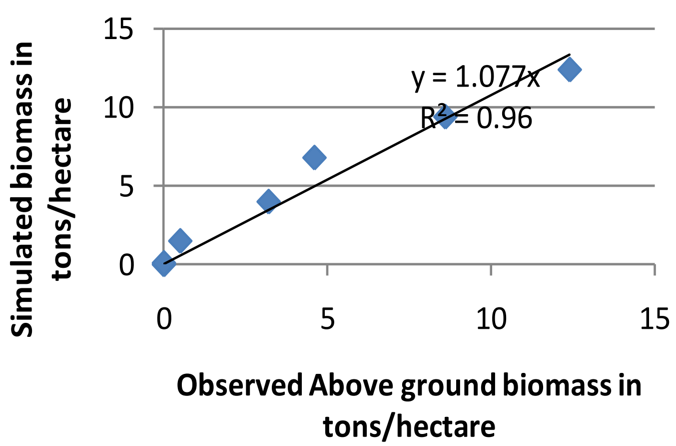

Figure 6. Observed versus simulated regression analysis biomass for treatment 1.

harvest index, the yield became 9.46 $Mg.ha^{-1}$ which was close to what was observed. The harvest Index was close to 80% obtained in Bangladesh where cabbages were grown using both inorganic and organic fertiliser under black polythene mulch (Sarker et al., 2003). The calibrated parameters for the study area have been summarized in Table 5.

Assessment of the model performance after calibration

Results of the assessment of the goodness of fit of model simulations for canopy cover, biomass and yield for treatment 1 are presented in Table 6. Nash-Sutcliffe model Efficiency (EF) compares the predicted values to the average value of measurements. If EF is less than zero, the model predicted values worse than simply using the observed mean. Coefficient of residuals (CRM) is a measure of the tendency of the model to overestimate or underestimate the measurements. A negative CRM shows a tendency to overestimate. Optimally, CRM should be very close to zero (Nash and Sutcliff, 1970).

The results of Table 6 show that the model simulations of final aboveground biomass and canopy matched the observations very well. The negative values for coefficient of residuals showed that the model overestimated the canopy and biomass.

Validation of biomass

Without any further adjustments to the calibrated model parameters, the above ground biomasses of the remaining 8 treatments were simulated. The simulated and observed final above ground biomass were compared. The results are presented in Figure 7. The results showed that y=1.1677x but the desirable line should be y=x, this means that the model overestimated the biomass though with high coefficient of determination.

Yield validation

The dry yields from the remaining 8 treatments (Table 7) were considered for validation of simulated dry head weight yield. Treatments 3, 4, 5, 6 and 9 had their yield overestimated, treatments 2 and 8 had their yields underestimated and therefore the model overestimated the yield as is normally the case with one-dimensional models (Sammis et al., 2012). The value of $R^2 = 0.7$ was obtained during validation of biomass (Figure 8). This value showed the relationship between observed and predicted biomass values was good.

Figure 8 shows the chart of the regression of simulated versus observed yields for eight treatments for irrigated cabbage.

Table 8 shows the assessment of the model performance during validation for biomass and yield simulation. The evaluation supports that AquaCrop model can simulate accurately cabbage yields under different irrigation treatments though it overestimated both the yield and biomass because of the negative values of the coefficient of residuals in Table 8. The robustness of AquaCrop is demonstrated by its ability to correctly simulate cabbage yields over a range from 6.6 to 9.4 tons/ha.

Conclusion

In this study, AquaCrop model was used to simulate cabbage yield, biomass and canopy to deficit irrigation in

Table 5. List of AquaCrop Model parameters calibrated for the Keiyo Highlands.

Parameter	Local Calibration	AquaCrop Default	Units
Maximum canopy cover (CC_x)	100	85	%
Water Productivity (WP_b^*) Normalised	17.0	17.0	g/m^2
Harvest Index (HI_o)	76	80	%

Table 6. Statistical parameters for the model performance during calibration.

Parameter	R^2	Root mean squared error	Efficiency of the model	Coefficient of residuals	Number of sample data points
Canopy	0.92	12.19%	0.99	-0.07	7
Biomass	0.96	0.38 ton/ha	0.94	-0.17	7
Ideal	1.0	0.0	1.0	0.0	

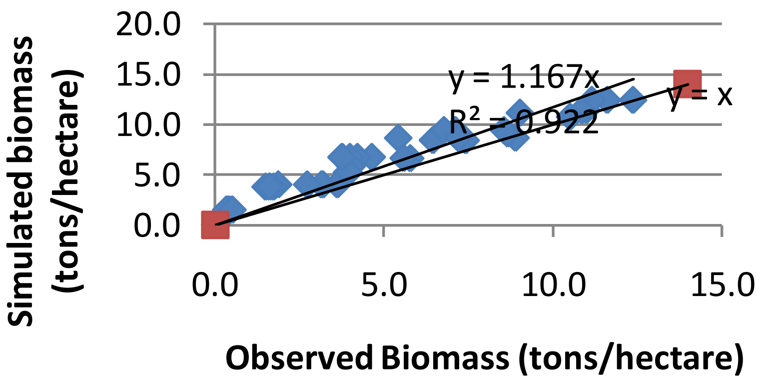

Figure 7. Simulated versus above ground biomass during validation.

Table 7. Simulated and observed dry yields in each treatment.

Dry yields	T2	T3	T4	T5	T6	T7	T8	T9
Observed	6.7	9.0	8.2	7.5	9.1	8.7	7.5	7.9
Simulated	6.6	9.5	8.7	8.5	9.5	8.7	6.9	8.2

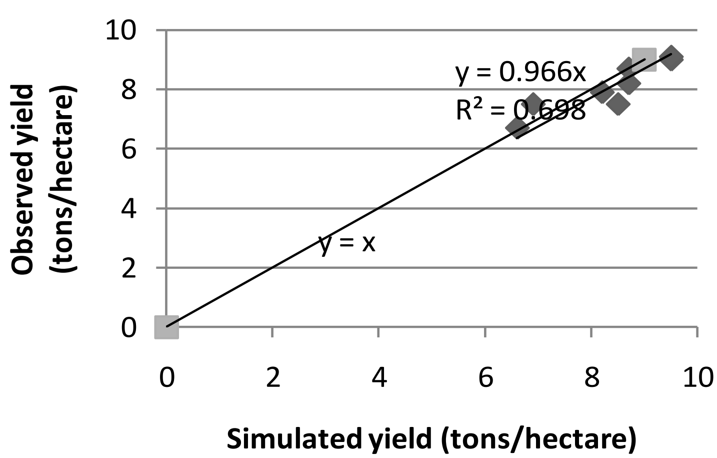

Figure 8. Observed and Simulated yield during validation.

Table 8. Statistical Parameters for the model performance during validation.

Parameter	R^2	Root Mean Squared Error	Efficiency of model	Coefficient of residuals	Number of sample data points
Biomass	0.92	1.4 tons/ha	0.84	-0.32	56
Yield	0.70	0.51 ton/ha	0.89	-0.03	8
Ideal	1.0	0.0	1.0	0	

Keiyo Highlands. A field experiment was done in 2011/2012 dry season. The results showed that AquaCrop model performed well under deficit irrigation. The cabbages at the field received same fertility, weeding and pest and diseases management. In this study water productivity of 17 g/cm^2 and Harvest index of 76% were found for cabbages.

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