Electronic Supplementary Material (ESI) for Environmental Science: Processes & Impacts.

Supplementary document to:

Agricultural livelihoods in coastal Bangladesh under climate and environmental change - A model framework

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S1: Brief overview of the extended CROPWAT model

This annex describes the extended CROPWAT model. The extended CROPWAT model uses the water availability calculations of the original CROPWAT model [1]. The key parameters and variables are listed in Table S1.

Water may enter the soil through the ground surface from rainfall or irrigation and leave as a result of evapotranspiration by plants. For the plant root zone, soil wetting and drying the water balance may be written over a long time period as

$$\sum(R + I - RO) - \sum ET + S - RE \approx 0$$

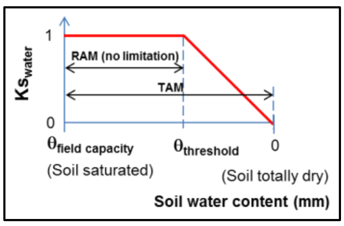
where *R* is the rainfall, *I* is the irrigation water, *RO* is the runoff, *ET* is the actual evapotranspiration, *S* is the change in stored water within the soil, and *RE* is the net recharge from the surrounding soil. Evapotranspiration is a function of the interactions between the elements of the plant–soil–atmosphere system. A simplified approach to estimate *ET* is to define a standard crop and soil condition so that evapotranspiration is then a function only of climate. Potential evapotranspiration can be estimated with reasonable confidence using the Penman–Monteith equation [2].

The purpose of a water balance calculation is to estimate changes in soil water content, which are related to the change in the volume of water stored within the soil, S. S is usually expressed as the soil moisture deficit (*SMD*), calculated in mm. A soil with zero *SMD* is at 'field capacity', that is, the equilibrium water content within a soil free to drain downward under gravity. For many soils, *SMD* = 0 mm usually occurs 1–2 days after rainfall. The soil moisture deficit changes dynamically in response to the inflows and outflows of water in the field. However, more rain leads to a significant water surplus in the monsoon months, resulting in runoff, and a water deficit during the dry season, which may lead to the vegetation becoming stressed. In the latter case, the actual rate of evapotranspiration is likely to fall below the potential evapotranspiration calculated using the Penman– Monteith equation, because a condition is reached whereby the residual soil moisture is not readily accessible by plants.

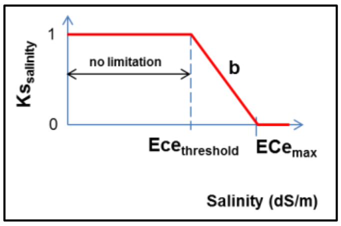
For the purposes of calculation, it might reasonably be further assumed that the inputted rainfall + irrigation water*,* infiltrates until the ground is at field capacity (i.e. the runoff *RO* is zero), after which the remaining input water runs off. Assuming that the vegetation is not stressed, the actual evapotranspiration (*ET*) is calculated by scaling the potential evapotranspiration ($ET_{potential}$) calculated using the Penman–Monteith equation by a crop factor Kc specific to the vegetation type. In calculating the actual evapotranspiration it is necessary to consider not only the total available water in the active root zone, *TAW* (i.e. that not bonded to the surface of the clay particles, $TAW = \Phi e * Zr$), but also the remaining readily available water, *RAW* (i.e. that which the plants can access without stress; $RAW = p * TAM$). Both *RAW* and *TAW* are expressed as volumes of water per unit area within the zone of drying, and therefore have units of mm, the same as the soil moisture deficit (*SMD*). While the *SMD* is less than the *RAW*, it can be assumed to that no water limitation occur for the actual crop. When the *SMD* exceeds the *RAW*, the water stress is assumed to increase linearly in proportion to the ratio of non-readily available water (*TAW – RAW*) extracted:

$0 \le SMD < RAW \qquad Ks_{water} = 1$

$SMD \ge RAW \qquad Ks_{water} = \dfrac{TAM - SMD_i}{TAM - RAM}$



The above paragraphs described the basis of the original CROPWAT model that only considers water availability. In the present study, the CROPWAT model was extended to consider the effect of soil salinity, air temperature and atmospheric fertilisation. **Soil salinity** is now modelled with the FAO56 equation [2] (pp.176-177). Salinity is not limiting the crop growth until a user defined threshold is reached ($ECe_{treshold}$). Beyond this point, the limitation caused by salinity is linearly increasing until the crop is not able to photosynthesise anymore (ECe_{max}).



$ECe_i \leq ECe_{threshold}$ $$Ks_{salinity} = 1$$

$ECe_i > ECe_{threshold}$ $$Ks_{salinity} = \frac{ECe_{threshold}}{K_y * 100} * \left(ECe_i - ECe_{threshold}\right)$$

The **atmospheric CO_2 fertilisation** is captured in the extended CROPWAT model, but using the equations of the FAO Aquacrop model [3] (version 4.0, Chapter 3: Calculation procedure, pp.86-87).

$CO_2 \leq 369.41$ ppm $$Ks_{CO2} = \frac{\frac{CO2_i}{369.41}}{1 + (CO2_i - 369.41) * 0.000138}$$

369.41 ppm $< CO_2$ & $CO_2 \leq 550$ ppm $$Ks_{CO2} = \frac{\frac{CO2_i}{369.41}}{1 + (CO2_i - 369.41) * \left[(1-w) * 0.000138 + w * \left(0.2 * 0.000138 + (1-0.2) * 0.001165\right)\right]}$$

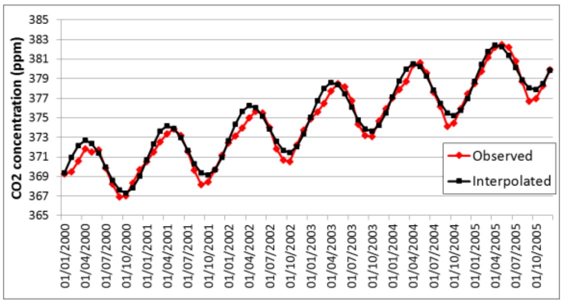
where $$0 \leq w = \frac{550 - CO2_i}{550 - 369.41} \leq 1$$

$CO_2 > 550$ ppm $$Ks_{CO2} = \frac{\frac{CO2_i}{369.41}}{1 + (CO2_i - 369.41) * \left(0.2 * 0.000138 + (1-0.2) * 0.001165\right)}$$

Since there is some intra-annual variability in atmospheric CO_2 concentrations, the annual observed CO_2 concentration values are interpolated by using a sinusoid function:

$$CO_{2,calculated,Month} = CO_{2,observed,y} + 3 * sin\left[radians\left(\frac{(Month - 1) * 360}{12}\right)\right] + Month * \frac{CO_{2,observed,y+1} - CO_{2,observed,y}}{12}$$

where *y* is the actual year, *y+1* is the following year, *Month* is the month number (e.g. March is 3). The equation was developed based on the Mauna Loa data (http://climexp.knmi.nl/data/iA1B.dat).



The **temperature stress** calculation is similar to the FAO Aquacrop calculation. It assumes an optimum temperature range ($T_{opt1} - T_{opt2}$), where growth is not limited by temperature, and beyond this range, growth limitation is linearly increasing until growth stops at the absolute limits (T_{min}, T_{max}).

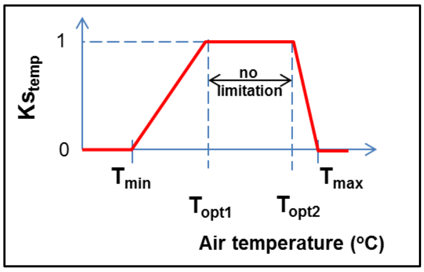
$T \leq T_{min}$ $$Ks_{temp} = 0$$

$T_{min} < T < T_{opt1}$ $$Ks_{temp} = \frac{Temp_i}{Temp_{opt1} - Temp_{min}} - \frac{Temp_{min}}{Temp_{opt1} - Temp_{min}}$$

$T_{opt1} \leq T \leq T_{opt2}$ $$Ks_{temp} = 1$$

$T_{opt2} < T < T_{opt2}$ $$Ks_{temp} = \frac{Temp_i}{Temp_{opt2} - Temp_{max}} - \frac{Temp_{max}}{Temp_{opt2} - Temp_{max}}$$

$T \geq T_{max}$ $$Ks_{temp} = 0$$



The **actual yield** of the particular crop, expressed as kg ha^{-1}, is the main output of the extended CROPWAT model. The calculation of the actual yield is followed by the FAO56 methodology [2] by assuming an equal weight of water, salinity, temperature and atmospheric fertilisation limitations in the actual evaporation (*ET_{actual}*) calculation. This actual evaporation is then used to calculate first the yield reduction and then the actual (or farmers') yield:

$$ET_{actual} = ET_{potential} * Ks_{water} * Ks_{salt} * Ks_{CO2} * Ks_{temp} * Kc$$

$$Yield\ Reduction = k_y * \left(1 - \frac{\sum ET_{actual,i}}{\sum ET_{potential,i}}\right)$$

$$Yield_{actual} = Yield_{potential} * (1 - Yield\ Reduction)$$

Table S1: List of key parameters and variables of the extended CROPWAT model

Symbol	**Unit**	**Description**
Kc	-	Crop coefficient. Selected from crop library, or Kc = 0.35 outside the crop development period
TAM	mm	Total Available Moisture
RAM	mm	Readily Available Moisture of the root zone
P	-	evaporation depletion factor
Zr	m	Rooting depth
Φe	-	Effective porosity of soil
$Irrig_{Water}$	mm	The amount of water used to irrigate the crop
$Irrig_{Amount}$	mm	The amount of fixed irrigation
$Irrig_{Frequency}$	days	The frequency of fixed irrigation
$Irrig_{Efficiency}$	%	The percentage of water that reaches the crop. (i.e. percentage that is not lost within the transport of water to the field)
TotalIrrigation	mm	Sum of all water used for irrigation
SMD	mm	Soil Moisture Deficit compared to field capacity
$Rain_{Eff}$	mm	The amount of precipitation that infiltrates into the soil
Rain	mm	Total daily precipitation
Imax	mm day^{-1}	Maximum daily infiltration rate of water into the soil
RunOff	mm	The amount of water that cannot infiltrate into the soil and thus creates a surface runoff
ET_{actual}	mm	Daily actual evapotranspiration rate
$ET_{potential}$	mm	Daily potential evapotranspiration rate
Ks_{water}	-	Water stress coefficient
Ks_{temp}	-	Temperature stress coefficient
Ks_{CO2}	-	Atmospheric fertilisation coefficient
Ks_{salt}	-	Salinity stress coefficient
ECe_i	dS m^{-1}	Soil salinity (mean electrical conductivity of the saturation extract for the root zone)
$ECe_{threshold}$	dS m^{-1}	electrical conductivity of the saturation extract at the threshold of ECe when crop yield first reduces below maximum yield
b	% (dS m^{-1})$^{-1}$	reduction in yield per increase in ECe
Temp	^oC	Mean daily air temperature
$Temp_{min}$	^oC	Minimum temperature needed to crop growth
$Temp_{opt1}$	^oC	Lower optimum temperature for crop growth
$Temp_{opt2}$	^oC	Upper optimum temperature for crop growth
$Temp_{max}$	^oC	Maximum temperature the crop can tolerate
ky	-	Yield response factor
$Yield_{actual}$	kg ha^{-1}	Actual yield of crop under current conditions
$Yield_{potential}$	kg ha^{-1}	Potential yield of crop under optimal environmental and management conditions
YieldReduction	-	Deviation from optimal yield

S2: Sensitivity analysis of the extended CROPWAT model

A preliminary sensitivity analysis is carried out to identify the most important crop parameters of the extended CROWAT model. The analysis uses a step-wise, local sensitivity analysis method[4] that is similar to the Crystal Ball methodology.

Table S2.1: The extended CROPWAT model parameters and the parameter ranges used in the sensitivity analysis (for the detailed description of the parameters, see the FAO56 guidelines)

Symbol	Unit	Description	Minimum	Maximum
Kc - initial	-	Crop coefficient	0.2	1.1
Kc - mid			0.9	1.1
Kc - late			0.2	1.1
p - initial	-	Evaporation depletion factor	0.2	0.7
p – mid			0.2	0.7
p - late			0.2	0.7
$ECe_{threshold}$	dS m^{-1}	Electrical conductivity of the saturation extract at the threshold of ECe when crop yield first reduces below maximum yield	1	8
b	% (dS $m^{-1})^{-1}$	Reduction in yield per increase in ECe	5	32
T_{opt1}	°C	Lower optimum temperature for crop growth	$T_{min}+\frac{T_{opt2}-T_{min}-1}{11}$	$T_{opt2}-1$
T_{opt2}	°C	Upper optimum temperature for crop growth	$T_{opt1}+\frac{T_{max}-T_{opt1}-1}{11}$	$T_{max}-1$
Ky	-	Yield response factor	0.7	1.3
Porosity	-	Effective porosity of soil	0.1	0.55
MaxInfiltration	mm day^{-1}	Maximum daily infiltration rate of water into the soil	10	100
LeachingFraction	-	Leaching fraction of soil	0.1	0.5

Fourteen parameters were selected to be included in the sensitivity analysis and these parameters were varied in between the selected parameter range (Table S2.1), starting from the minimum and ending at the maximum value with a step-change of 10 percent. The extended CROPWAT model was run with each of parameter value, and a normalised sensitivity index was calculated (e_p) after each model run for each crop parameter (*i*):

$$e_{p,i}=\frac{\partial O_i}{\partial P_i}\frac{P_i}{O_i}\approx\frac{\Delta O_i}{\Delta P_i}\frac{P_i}{O_i}=\frac{O_{i,j}-O_{i,0}}{1.1P_i-P_i}\frac{P_i}{O_{i,0}}=\frac{O_{i,j}-O_{i,0}}{0.1O_{i,0}}$$

, where *O* is the model output value, *P* is the input parameter value, *i* represent one of the crop parameters, *j* represents one of the sensitivity model runs and *0* represents the initial model run with the minimum parameter value. Thus the e_p can only vary in between -1.0 and +1.0.

The sensitivity analysis was carried out for 18 crops (out of the 36 crop of the crop library), for 44 randomly selected upazilas representing all three cropping seasons and all districts of the study area and for 30 years (1981-2010). For each crop, the e_p value was calculated for all simulated years. Finally, the mean of these e_p values are calculated for each crop parameter and for each cropping season separately. The results of the sensitivity analysis are presented and discussed in the main text in Section 4a.

This sensitivity index assumes linear conditions that rarely happen in reality and ignores parameter interactions. Therefore the results of this sensitivity analysis can only be considered as rough estimate, until a more thorough, global sensitivity analysis is done. However, such an analysis is still useful to provide a rapid preliminary assessment of the model that requires low computing resources.

S3: Calibration of the extended CROPWAT model

The calibration of the extended CROPWAT model is based on a routine in which the possible parameter space is explored to find a best fit to the observed farmers' yield data. Some crop properties measured in Bangladesh was made available (see Table S3.1), therefore, these properties were fixed in the calibration. Table S3.2 summarises the model parameters and the parameter ranges used in the optimisation routine.

Table S3.1: Crop properties

Historical / Present crops						
Crops	**Variety**	**Crop duration (days)**	**Crop growing period**	**Temp. tolerance (°C)**	**Salinity tolerance (dS m^{-1})**	**Potential yield (tons ha^{-1})**
T. Aman	HYV	110-145	15Jul - 15Nov	20-38	4-6	2.5 - 2.7
	Local	130-150	1 Aug - 31 Dec	20-38	2-6	1.60 - 1.65
T. Aus	HYV	130-135	15May - 15Aug	20-38	4-6	3.5 - 4.0
	Local	120-140	10May - 15Aug	20-38	2-4	1.75 - 1.85
Boro	HYV	140-165	15Jan - 15 May	11-38	4-8	5.5 - 6.0
Chilli	Local	160-170	Feb/Mar - June/Aug	20-30	3-5	1.5 - 1.7
	Hybrid	180-200	Sept/Oct - Dec/April	20-30	3-5	2.5 - 3.0
Grass pea	HYV	125-130	Nov/Dec - Mar/April	14-22	5-10	1.7 - 1.9
Potato	HYV	85-100	15 Nov - 20 Feb	15-25	5-7	35 - 40
Wheat	HYV	105-110	25Nov - 31March	10-32	4-6	4.0 - 5.0

Note: T – transplanted; HYV – high yielding variety

Table S3.2: The extended CROPWAT model parameters and the parameter ranges used in the optimization routine (for the detailed description of the parameters, see the FAO56 guideline)

Symbol	Unit	Description	Minimum	Maximum
Kc - initial	-	Crop coefficient	0.2	1.1
Kc - mid			0.9	1.1
Kc - late			0.2	1.1
p - initial	-	Evaporation depletion factor	0.2	0.7
p – mid			0.2	0.7
p - late			0.2	0.7
Zr	m	Rooting depth	CROPWAT 8.0 library value for the specific crop	
$ECe_{threshold}$	dS m^{-1}	Electrical conductivity of the saturation extract at the threshold of ECe when crop yield first reduces below maximum yield	see Table S3.1	
b	% (dS m^{-1})$^{-1}$	Reduction in yield per increase in ECe	calculated from Table S3.1	
T_{min}	°C	Minimum temperature needed to crop growth	see Table S3.1	
T_{opt1}	°C	Lower optimum temperature for crop growth	$T_{min} + \frac{T_{max} - T_{min}}{4}$	$T_{max} - \frac{T_{max} - T_{min}}{4}$
T_{opt2}	°C	Upper optimum temperature for crop growth		
T_{max}	°C	Maximum temperature the crop can tolerate	see Table S3.1	
Ky	-	Yield response factor	0.7	1.3
$Yield_{potential}$	tons ha^{-1}	Potential yield of crop under optimal environmental and management conditions	see Table S3.1	
Length of growth stages	days		see Table S3.1	
Planting & harvesting date	date		see Table S3.1	

The parameter optimisation routine was done for the year 2010 because both the observed farmers' yield data and the used soil salinity data were considered the most reliable in that year. The actual model run was done at Upazila level and the Upazila-level results were averaged over for the nine districts. These district average yield values were compared with the observations, and the Root Mean Square Error (RMSE, %) goodness of fit coefficient was calculated for the entire study area with the following equation.

$$RMSE = \frac{100}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

where O_i is the i[th] observed crop yield (i.e. observed district-level farmers' yield), P_i is the i[th] modelled crop yield (i.e. district average of simulate farmers' yields), $\bar{O}$ is the mean of the observed crop yield, and n is the number of data points (i.e. the number of districts where observations were available for the specific crop).

During the optimization, the extended CROPWAT model was run numerous times, searching for the local minimums of RMSE. The best one hundred parameter sets (i.e. with the smallest RMSE for 2010) was recorded. These one hundred parameter sets were then used to test the model performance for the year 1990 and 2000 (district level observations) by calculating the RMSE values for each one hundred model runs. Finally, the parameter set that fit best all three years (i.e. by averaging the 1990, 2000 and 2010 RMSE values) was selected for each crop as the final set of parameters. This final parameter set was further tested with observations for nine Upazilas for the years of 2000, 2005 and 2010 to further validate the selected parameter set.

Table S3.3 summarises the calibrated parameter sets and the RMSE values and Figures S3.1-S3.7 plot the results for most of the crops. The optimisation for 2010 at district level resulted in a good fit in most cases (see criteria below Table S3.2). Representation of the year 2000 conditions was mostly acceptable but district-level simulation results for the year 1990 almost always greatly deviated from the district level observations. On the other hand, the upazila-level simulations of the final parameter set showed good correlation with the observations for both 2000, 2005 and 2010 years. The deviation from the observed values for 1990 can be caused by a mixture of four issues:

1. Model structural error and parameter uncertainty
2. Uncertainty around the observed farmers' yield:
    a. the way it was collected and entered into databases might have changed over time;
    b. data for different varieties are mixed up in one average yield value (for example T.Aus HYV) and the proportion of these varieties in the statistics have changed over time;
3. The management of the crops could have drastically improved since 1990, but the CROPWAT model does not any include management related equations/parameters apart from irrigation.
4. Soil salinity is highly spatially and temporally variable in the coastal zone of Bangladesh, and observed, homogenous soil salinity timeseries are not available. The present study used average upazila-level, yearly salinity values for 1971, 2000 and 2009 and carried out a linear interpolation in between the observed values. Finally, the seasonality of soil salinity was assumed to be the same as for river salinity. This approach holds considerable uncertainties for the model results.

The Upazila-level simulated yields are generally well representing the observations. This supports the model setup, namely that the simulations are done at Upazila level. The fit to observations was not so good for some minor crops, such as potato and grass pea, but they are generally accounted for less than 10 percent of the total agriculture area in coastal Bangladesh. Unfortunately, the re-calibration of these crops would require further data that is currently not available. Therefore, the calibrated model parameters were accepted because (i) the 2000-2010 period was acceptably represented in the simulations both the district and Upazila levels for most crops and (ii) the three rice type, the most important crops in terms of area (Boro – 50%, T.Aus – 80%, T.Aman – 95% of total area in 2010), are well represented in the simulations. The results before 2000, however, have to be considered with care as deviations are great from the observations and it is not possible to know if this is caused by model structural error or uncertainty in the observations.

Table S3.3: Results of the calibration exercise

	Goodness-of-fit results						Calibrated model parameters								
Crops	**RMSE** (2000, Upazila, %)	**RMSE** (2005, Upazila, %)	**RMSE** (2010, Upazila, %)	**RMSE** (1990, district, %)	**RMSE** (2000, district, %)	**RMSE** (2010, district, %)	***Kc,ini***	***Kc,mid***	***Kc,late***	***Ky***	***p-ini***	***p-mid***	***p-late***	***Topt1***	***Topt2***
T. Aman (local)	14.1	9.7	4.1	8.2		2.3	1.1	1.1	1.1	1.1	0.7	0.45	0.2	25	27
T Aman (HYV)	8.8	8.8	8.6	60.3	28.1	6.9	1.1	1.1	1.1	0.7	0.2	0.45	0.2	33	35
T.Aus (local)	38.8	5.2	5.9	6.8		2.7	0.2	1.1	1.1	1.1	0.7	0.2	0.2	29	35
T Aus (HYV)	16.0	18.3	10.1	47.4	17.9	9.6	1.1	1.1	1.1	0.7	0.2	0.7	0.2	25	27
Boro (HYV)	8.7	12.0	11.0	50.3	13.6	11.9	1.1	1.1	1.1	0.9	0.7	0.45	0.2	18	21
Chilli (local, rabi)				15.4		8.4	1.1	0.9	1.1	0.9	0.2	0.45	0.55	23	24
Chilli (hybrid, rabi)	18.7	14.4	10.4	58.3	32.9	7.4	1.1	0.9	1.1	0.7	0.2	0.45	0.55	23	24
Grass pea (HYV)	48	26	29	123	44	24	0.2	1.1	0.7	0.9	0.2	0.2	0.45	16	17
Potato (HYV)	76	49	65	315	207	70	1.1	1.1	0.2	1.3	0.2	0.2	0.45	22	23
Wheat (HYV)	28.4	28.8	24.6	144.1	99.8	22.0	1.1	1.1	0.2	1.1	0.2	0.45	0.55	26	28.5

Notes:

Colour	Goodness of fit
(green)	very good (<15%)
(blue)	acceptable (15-30%)
(orange)	fair (30-50%)
(red)	poor (>50%)
(white)	no observation

Figure S3.1: Observed and simulated yield (tons ha^{-1}) of Transplanted Aman (HYV)

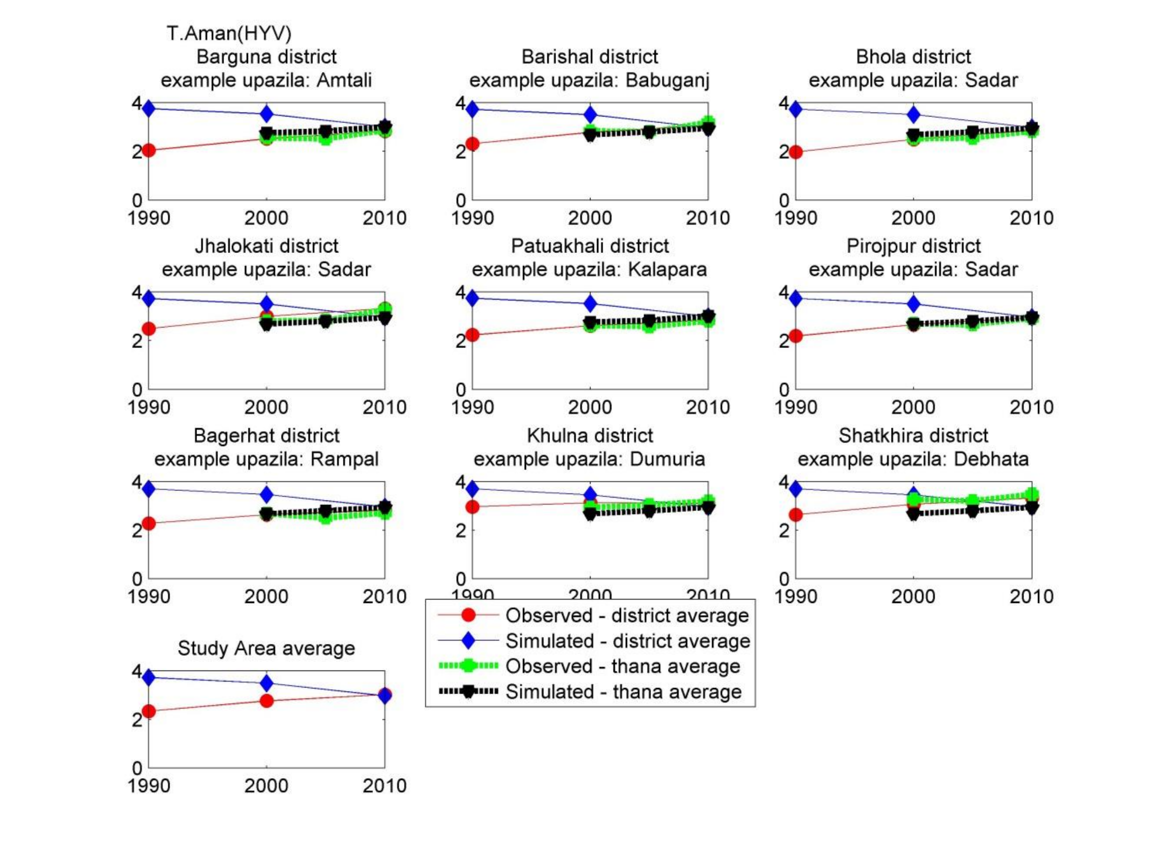


Figure S3.2: Observed and simulated yield (tons ha^{-1}) of Transplanted Aus (HYV)

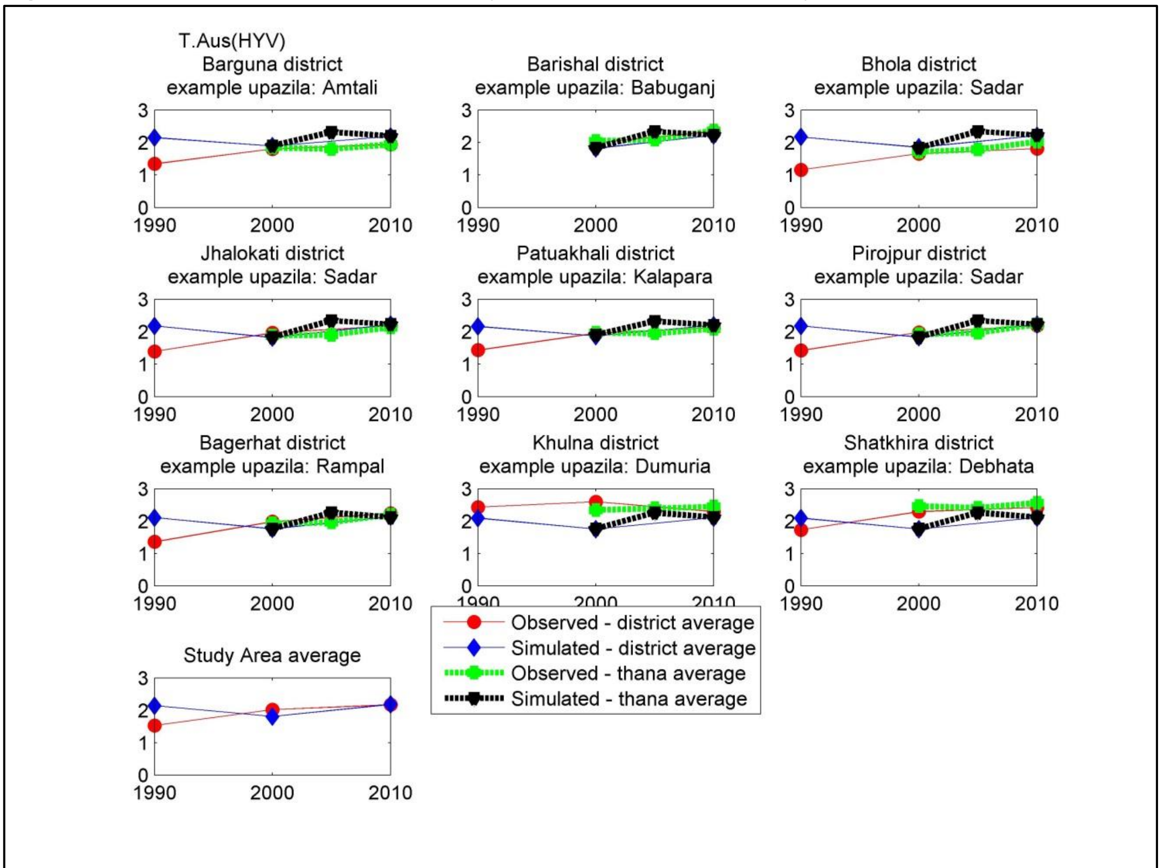


Figure S3.3: Observed and simulated yield (tons ha-1) of Boro (HYV)

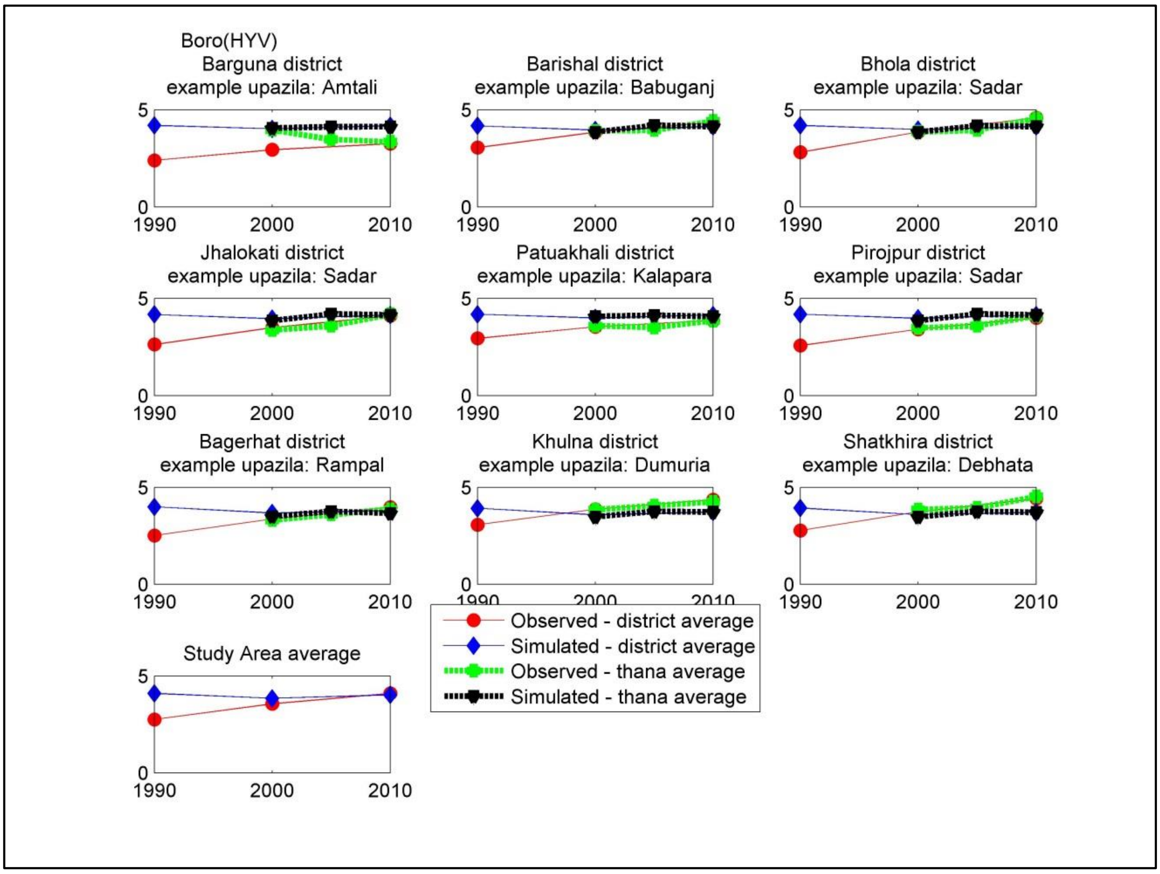


Figure S3.4: Observed and simulated yield (tons ha^{-1}) of Chilli (Hybrid, Rabi season)

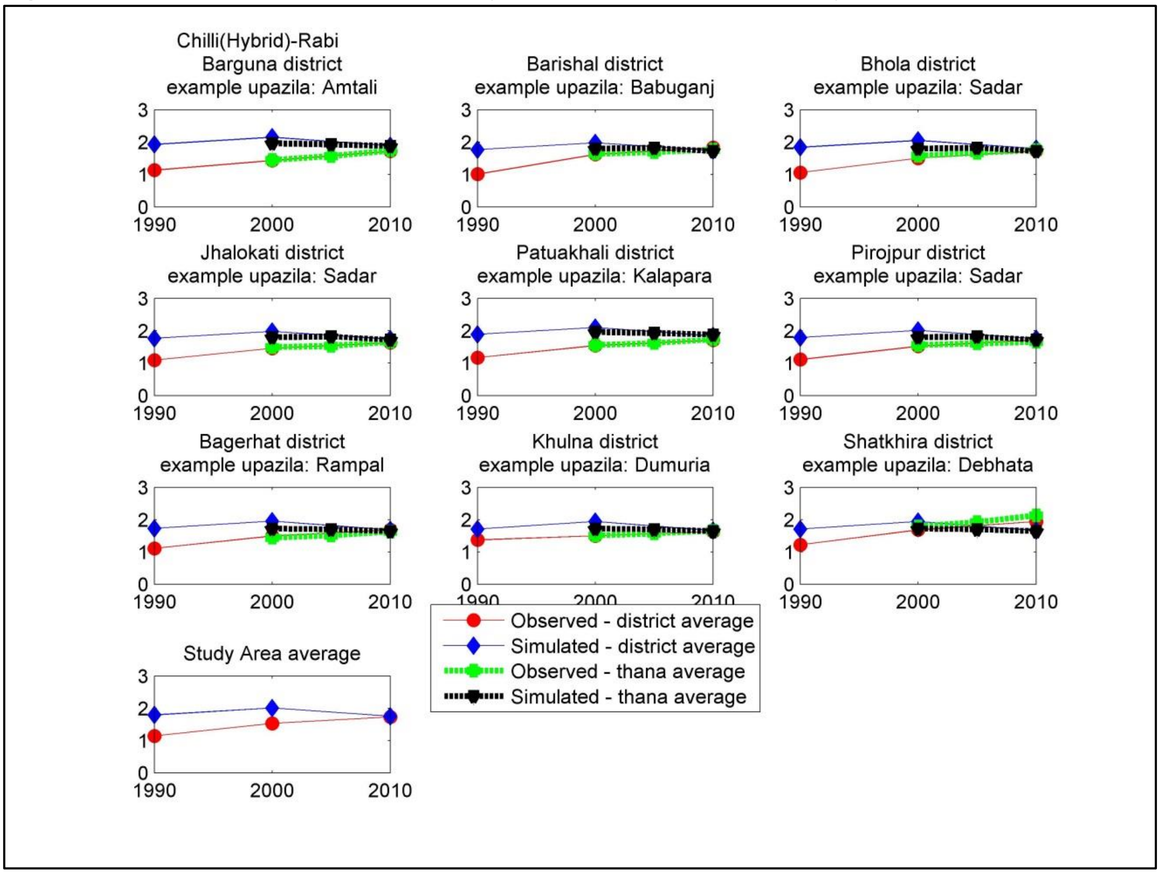


Figure S3.5: Observed and simulated yield (tons ha^{-1}) of Grass pea (HYV)

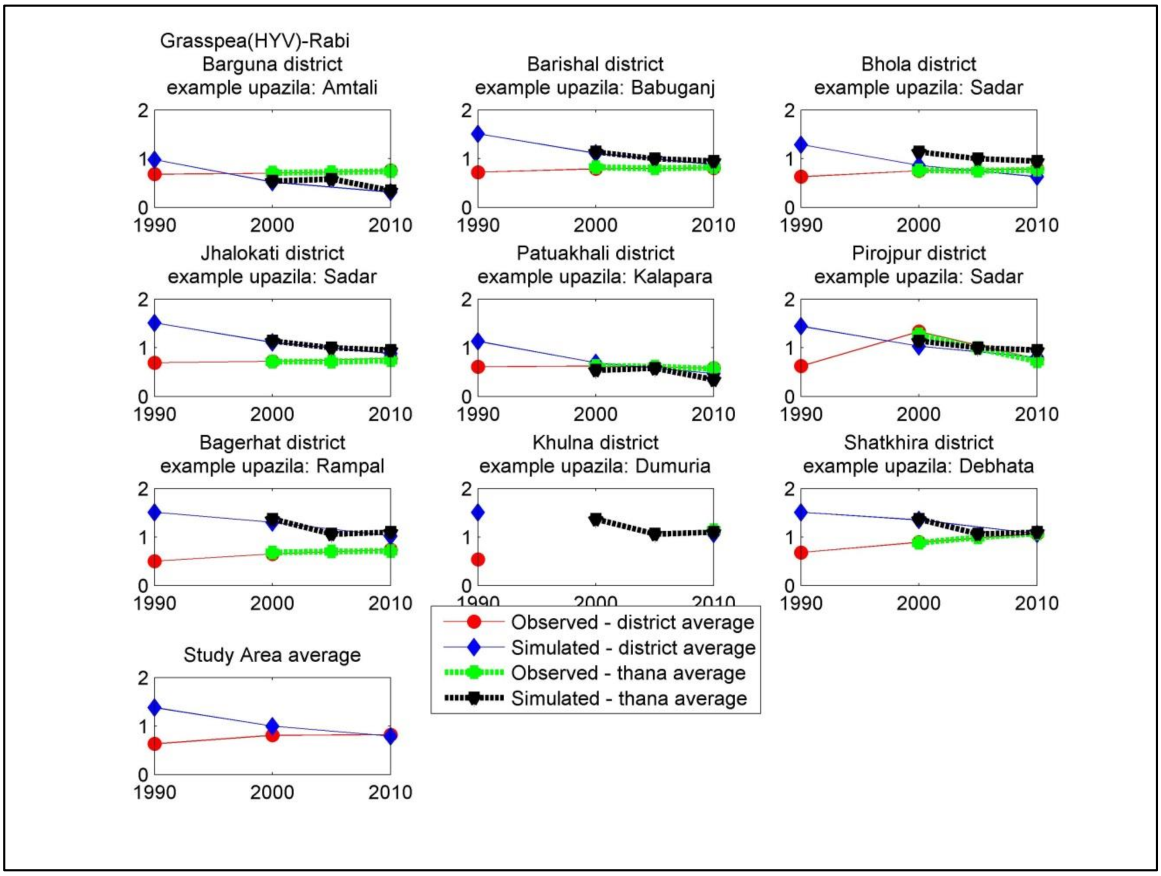


Figure S3.6: Observed and simulated yield (tons ha^{-1}) of Potato (HYV, Rabi season)

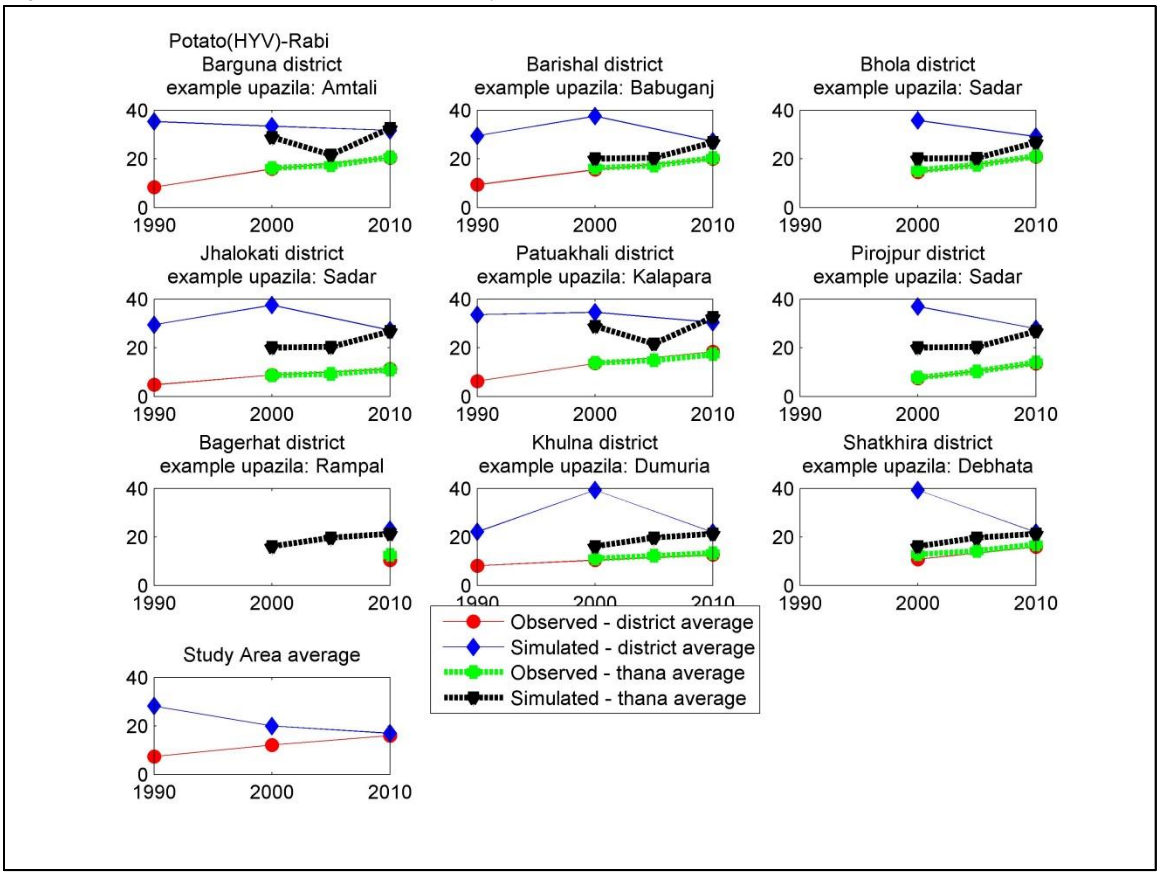
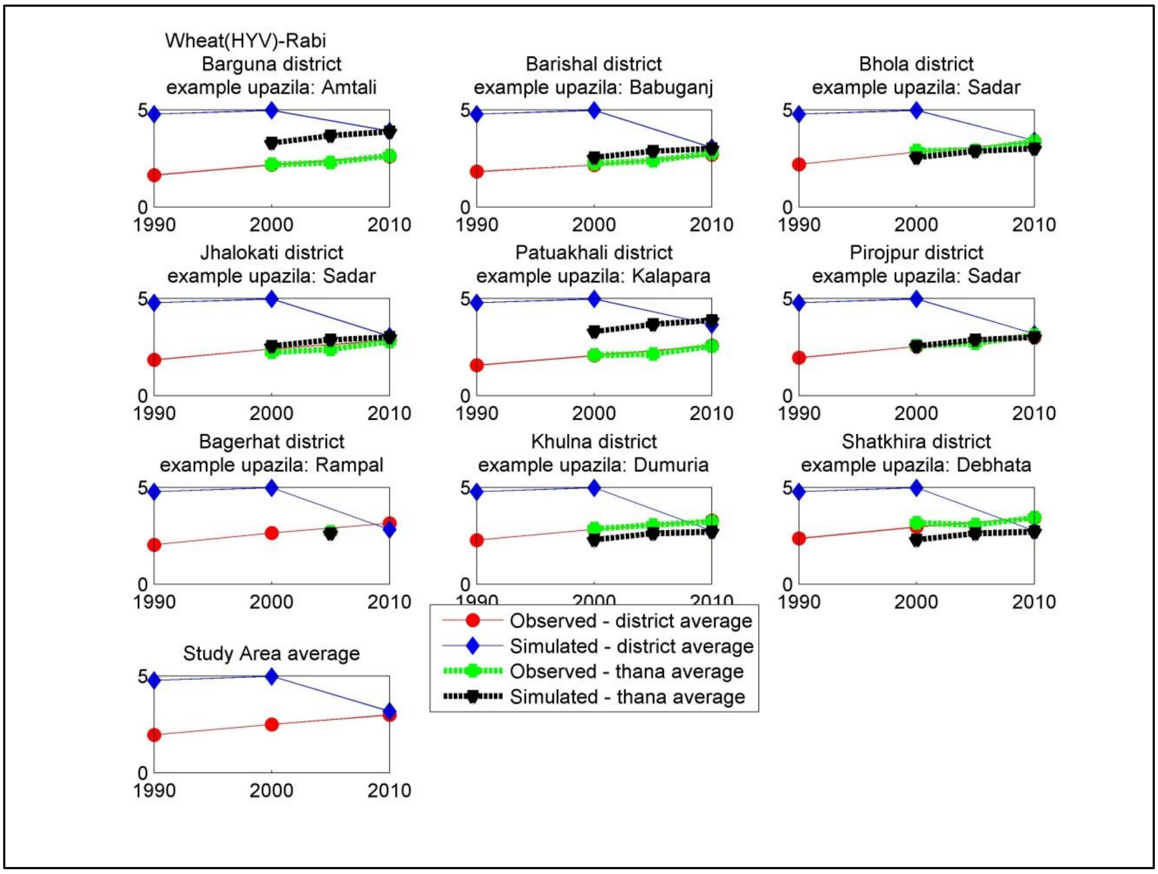


Figure S3.7: Observed and simulated yield (tons ha^{-1}) of Wheat (HYV, Rabi season)



References

1. D. Clarke, *CropWat for Windows : User Guide*, University of Southampton, 1998.
2. R. G. Allen, L. S. Pereira, D. Raes and M. Smith, *FAO Irrigation and Drainage Paper - No. 56: Crop Evapotranspiration (guidelines for computing crop water requirements)*, FAO, Water Resources, Development and Management Service, Rome, Italy, 1998.
3. D. Raes, P. Steduto, T. C. Hsiao and E. Fereres, *AquaCrop Version 4.0: Chapter 3 Calculation procedures*, FAO, Land and Water Division, Rome, Italy, 2012.
4. M. Rode, U. Suhr and G. Wriedt, *Ecological Modelling*, 2007, **204**, 129-142.