

Assessment of climate change impact on crop yield and irrigation water requirement of two major cereal crops (rice and wheat) in Bhaktapur district, Nepal

Lajana Shrestha and Narayan Kumar Shrestha

ABSTRACT

Rice and wheat are major cereal crops in Nepal. Climate change impacts are widespread and farmers in developing countries like Nepal are among the most vulnerable. A study was carried out to assess the impact of climate change on yield and irrigation water requirement of these cereal crops in Bhaktapur, Nepal. Laboratory and soil-plant-air-water analysis showed silt-loam being the most dominant soil type in the study area. A yield simulation model, AquaCrop, was able to simulate the crop yield with reasonable accuracy. Future (2030–2060) crop yield simulations, on forcing the Providing Regional Climates for Impacts Studies (PRECIS) based on regional circulation model simulation indicated decreased (based on HadCM3Q0 projection) and increased (based on ECHAM5 projection) yield of monsoon rice for A1B scenario, and rather stable yield (for both projection) of winter wheat. Simulation results for management strategies indicated that the crop yield was mainly constrained by water scarcity and fertility stress emphasizing the need for proper water management and fertilizer application. Similarly, a proper deficit irrigation strategy was found to be suitable to stabilize the wheat yield in the dry season. Furthermore, an increase in fertilizer application dose was more effective in fully irrigated conditions than in rainfed conditions.

Key words | AquaCrop, climate change, PRECIS, rice, wheat

Lajana Shrestha

Narayan Kumar Shrestha (corresponding author)
Center for Post-Graduate Studies, Nepal
Engineering College (neccPS), Kathmandu,
Pokhara University,
Nepal
E-mail: shrestha.narayan@hotmail.com

Narayan Kumar Shrestha

Faculty of Science and Technology, Athabasca
University, Edmonton,
Alberta,
Canada

INTRODUCTION

It is increasingly becoming clear that climate change is a real phenomenon and human activities such as burning of fossil fuel, deforestation, and so on are primarily to blame. As such, the recent anthropogenic emission of greenhouse gases is at its highest level (IPCC 2014). The impacts of increased temperature and elevated CO₂ level, intense or no rainfall, are widespread on natural systems and on humans (IPCC 2000, 2014). Water resources are affected, and hence the agricultural sector which could have long-term effects on food security (Malla 2008; IFPRI 2009). It is evident that increase in temperature and carbon dioxide

(CO₂) have a positive impact on some crops, but the nutrient levels, soil moisture conditions, water availability for irrigation, and other crop-related conditions should be favorable in order to have better crop yield (Maximay 2014). Moreover, changes in precipitation pattern such as intense rainfall during a particular month are becoming more frequent and such events could have a devastating effect on crop production especially if they occurred in a sensitive phase of the crop, e.g., the flowering stage (Joshi *et al.* 2011).

All these events associated with climate change would pose further stress on farmers to produce more and more food for an increasingly growing and wealthier population (FAO 2011). The case is even more severe in peri-urban areas like Bhaktapur district, Nepal, which has experienced rapid urbanization of late (Shrestha *et al.* 2013b). To cope

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

doi: 10.2166/wcc.2016.153

with such adverse effects (of climate change), different adaptive management practices especially applying proper fertilizer dose and water application need to be adopted. Furthermore, adaptation practices such as shifting of crop plantation date, adjusting cropping area and intensity might need to be considered (Iizumi & Ramankutty 2015).

There have been some studies which have quantified the impact of climate change on cereal crop yields at regional and national scale. For instance, Lal (2007) reported a decrease of 4–10% in cereal crop yield by 21st century in South Asia. Similarly, Shrestha *et al.* (2014) reported, based on a study in Myanmar, that future climate condition would increase the paddy rice yield and would thus increase the food security in the region. Acharya & Bhatta (2013) used a quantitative modelling approach to calculate the impact of climate change on agricultural gross domestic product of Nepal, and found positive impact due to increased precipitation in future. Karn (2014) reported a decrease of 4.2% in rice yield based on analysis made on 20 major rice growing district of Nepal. Palazzoli *et al.* (2015) carried out a study based on a physically based model in Indrawoti river basin of central Nepal, and found different estimates (–36% to +18% for wheat, and –17% to +12% for rice) of crop yield changes while using different future climate projection data. It is thus evident that very few studies have focused on peri-urban regions like Bhaktapur district.

In this context, this paper analyzes the impact of climate change on yield response of main cereal crops – rice and wheat in Bhaktapur district, Nepal. It also aims to find ways to stabilize the yield with plausible water and fertilizer application scenarios. An understanding of the impacts of recent climate trends on major cereal crops would help to anticipate impacts of future climate on the agriculture sector. We believe that the outcome of the study will facilitate in formulating suitable adaptation strategies to cope up with the adverse effects of climate change, thereby increasing food security of the district.

METHODS

Study area

The Bhaktapur district (Figure 1) is the smallest district of Kathmandu Valley, Nepal. Although peri-urban, the district

has about 80% of its total area as agricultural land (10,240 ha). Only 30% of the agricultural land has round-the-year irrigation facilities (Poudel *et al.* 2012). Because of the very fertile nature of the land, the district is also known as the grain and vegetable store of the valley. Rice, wheat, and maize are the major cereal crops of the district and are grown in land areas of 4,326, 3,665 and 1,793 ha, respectively. The annual production of these cereal crops is 4.5, 2.69 and 2.93 t/ha, respectively (Poudel *et al.* 2012).

Data collection

Several different techniques were applied for the data collection and will be discussed in the next sections.

Questionnaire survey, field visits and soil samples

Altogether 30 soil samples (see Figure 1) from different locations of the district were taken based on snowball sampling technique. Moreover, farmers of the sampled land were also supplied with questionnaires in order to collect information regarding farming practices, main factors affecting the plantation of crops, crop yield, variety of crops, crop phenological stages, and period, time and irrigation practices. To determine the soil texture class, collected soil samples were submitted to the Agricultural Technology Center (ATC), Nepal. Although the soil samples were taken from 30 cm depth, uniform soil profile is considered as suggested by Shrestha (2014).

Climate data

Daily historical climate data were collected from the Department of Hydrology and Meteorology (DHM), Nepal, for the period 1979–2013 of nearby station named Tribhuvan International Airport (TIA), Nepal. It should however be noted that there exist several meteorological stations in and around the Kathmandu Valley. Considering the fact that the Bhaktapur district is the smallest district of the valley and the TIA station is the nearest to the district, and most of the other stations are lying either on foothills or on the hills, use of only one station (the TIA) located on a similar altitude as that of study area can be justified. The climate data included daily rainfall, maximum and minimum air temperature, sunshine hours, wind speed and relative humidity. Figure 2 shows time series plots of annual rainfall,

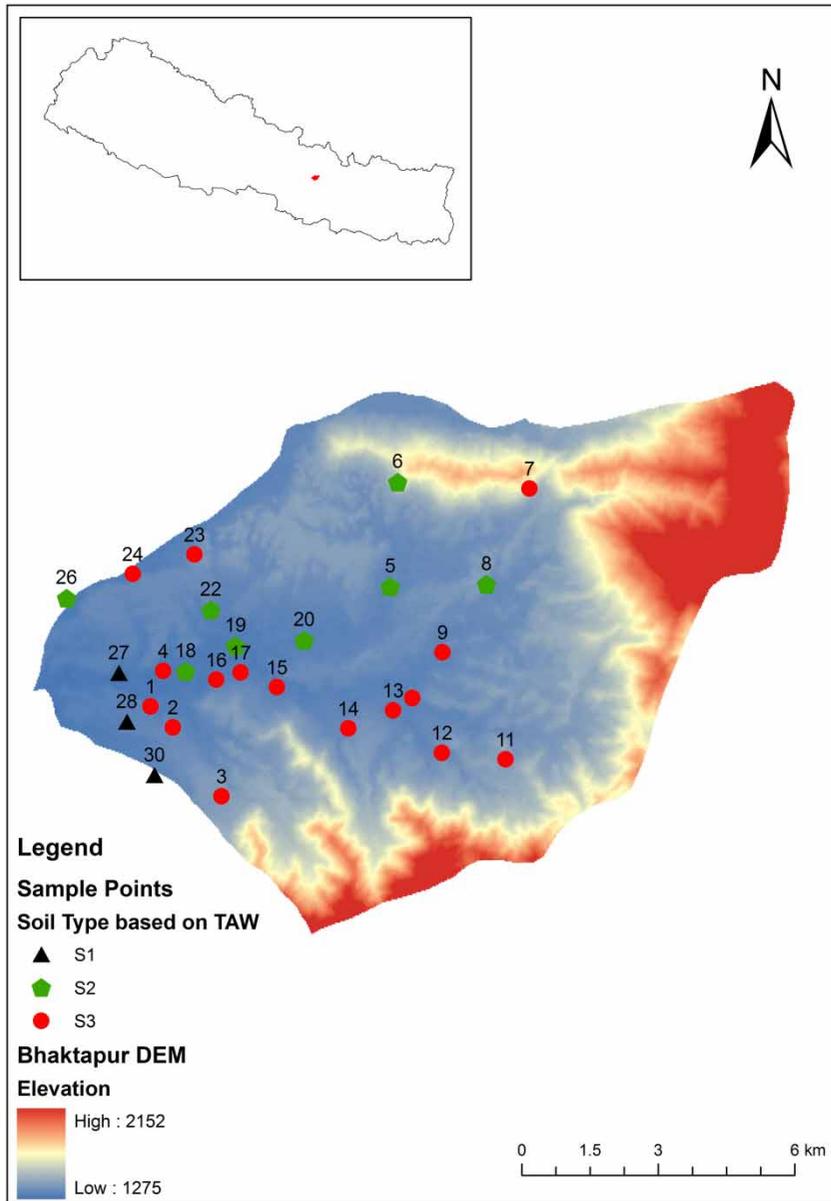


Figure 1 | The study area (Bhaktapur district) with soil sample points indicated by markers as per soil types: S1 (black triangle), S2 (green pentagon) and S3 (red circle). Also shown, in inset, is the map of Nepal and location of Bhaktapur district. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wcc.2016.153>.

and minimum and maximum temperature at the station during 1979–2013.

Simulators/models used

ETo calculator

The ETo calculator, developed by the Land and Water Division of the Food and Agriculture Organization (FAO), is

used to calculate the potential evapotranspiration (ETo). The tool is based on a theoretical method proposed by Penman and Monteith (Allen *et al.* 1998) to calculate the ETo. The tool requires several climatic data such as temperature (maximum and minimum), relative humidity, wind speed, solar radiation etc., at user defined time steps. In this study, the tool was run for a daily time scale. Besides calculating the ETo, temperature data are also produced in a format suitable for the AquaCrop model (see below for details on the model).

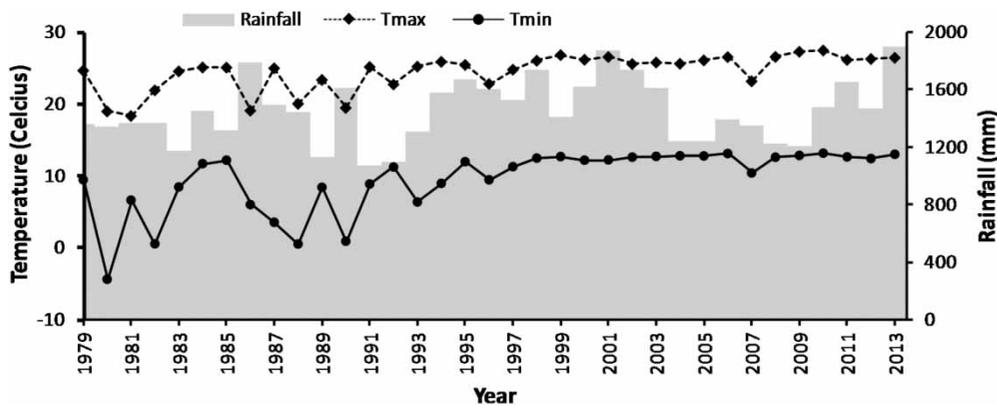


Figure 2 | Time series plot of annual rainfall volume (as grey column), and maximum (T_{max} , as black diamond) and minimum (as black circle, T_{min}) temperature at a meteorological station (Tribhuvan International Airport – TIA) used in the study.

Soil-plant-air-water model

Soil-plant-air-water (SPAW) is a model which is generally applied to simulate daily hydrologic water budgets of agricultural landscapes. The embedded hydrologic analysis involves the evaluation of soil water infiltration, conductivity, storage, and plant-water relationships (Saxton *et al.* 2006). Soil characteristics such as textural composition, organic matter content, as obtained from the laboratory tests, were supplied to the model which in turn simulated permanent wilting point, field capacity (FC), total available water (TAW), and saturated hydraulic conductivity (SAT) as outputs. These outputs are actually required by the AquaCrop model (see next section for details on the model).

AquaCrop

AquaCrop is a crop-water productivity model which relates the soil, crop and atmospheric components. The soil component requires soil horizons of different texture composition, and for each textural class, hydraulic characteristics (generally the results of SPAW model) are required. The atmospheric component requires rainfall (generally observed at a meteorological station), temperature (generally the result of ETo calculator), evapotranspiration (generally the result of ETo calculator), and carbon dioxide concentration (generally taken as default value of the year 2000 measured at Mauna Loa Observatory, Hawaii). The crop component requires information about the crop such

as phenology, crop cover, root depth, biomass production and harvestable yield, and field management conditions such as irrigation fertility, and field agronomic practices (Raes *et al.* 2012). The crop files for Nepal's general crops were adapted from the study of Shrestha (2014). The model was built up using the subsequent model outputs of the ETo calculator, SPAW model, and using information collected in the questionnaire survey. The model is then calibrated based on the actual yield, also obtained from the questionnaire survey.

Future climatic projection data

Future climate projection data were fetched from the Nepal Climate Data Portal (NCDP 2014) with spatial resolution of 25×25 km. The data were based on Providing Regional Climates for Impacts Studies (PRECIS), one of the widely used dynamical downscaling tools developed at Met Office and Hadley Center, United Kingdom. The tool uses the atmospheric component of the HadCM3 Global Climate Model – GCM (Gordon *et al.* 2000; Jones *et al.* 2004, as cited in NCDP 2014). Data of a Regional Climate Model (RCM) run in PRECIS with imposed Lateral Boundary Condition (LBC) as HadCM3Q0 and ECHAM5, both with A1B scenario (IPCC 2000), were fetched in the NetCDF format (NCDP 2014). The future climate data (2030–2060) would then be used for simulating field management strategies for future climate change scenarios. As such, average data of all pixels covering the study area were estimated using ArcGIS.

Tested management scenarios

Different water and fertilizer scenarios (Table 1) were formulated as plausible adaptation measures to cope with adverse climate change impact. The calibrated AquaCrop model was run to simulate the crop yield using these scenarios. Under water management scenario, rainfed (RF) and full irrigation (FI) conditions were formulated. These water management scenarios are currently practiced in the study area. Due to high household demand in the study area because of ever increasing population, and due to the need for allowing minimum discharge to maintain the ecological status of surface water, farmers are likely to face water scarcity and might not be able to use all the surface water sources for irrigation purposes in near future. Hence, another scenario (deficit irrigation) in which limited water is applied at the most sensitive growing phase of the crop (e.g. before and after flowering), is tested too. Deficit irrigation scheme is a rather promising and tested irrigation technique, especially in rain deficient conditions (Geerts *et al.* 2008, 2010; Geerts & Raes 2009; Shrestha *et al.* 2013c). As such, we tested two deficit irrigation scenarios – D1 and D2 (see description in Table 1). While RF and FI conditions are applicable for monsoon rice, the D1 and

D2 are only applicable for winter wheat. Under the fertilizer management scenarios, different fractions of fertilizer as per National Recommended Fertilizer Dose (NRFD) were formulated (Table 1). Finally, all possible permutations of water and fertilizer application scenarios were tested.

RESULTS AND DISCUSSION

Results from social survey

It was found that 100% of the farmers grow rice during the monsoon season (June to September), and the overwhelming majority (>80%) grow wheat during the winter season. During winter, the rest (20%) grow maize. The statistics indeed justified our selection of rice and wheat being two major cereal crops of the study area. Besides, 80% of the respondents reported that they waited for rainfall in order to sow the crops, and the rest (20%) first examined moisture content in the soil and then fixed a sowing date.

Respondents agreed that there had been a decrease in the crop yield, due to several factors including (see Figure 3): (a) spreading of disease (40%), (b) water scarcity (30%), (c)

Table 1 | Water and fertilizer management scenario used in the simulation

Crop	Water Management	Fertilizer Management
Monsoon rice	(a) RF	(a) 150% of NRFD/Non-limiting
	(b) Full Irrigation (FI): (Soil Water Content (SWC) maintained up to 100% FC)	(b) 100% of NRFD (c) 50% of NRFD (d) 0% of NRFD
Winter wheat	(a) RF	(a) 150% of NRFD/Non-limiting
	(b) Full Irrigation (SWC maintained up to 30% of FC)	(b) 100% of NRFD
	(c) Deficit Irrigation Strategy D1 (two application of 1/6 Net Irrigation Requirement (I_{net}) each before and around flowering)	(c) 50% of NRFD
	(d) Deficit Irrigation Strategy D2 (three applications of 1/6 I_{net} each, one before, around and after flowering)	(d) 0% of NRFD
NRFD: National Recommended Fertilizer Dose in which following chemical content is needed (MoAC 2010)		
Component	Fertilizer component required in rice (wheat) expressed in kg/ha	
Nitrogen	100 (100)	
Phosphorus	30 (50)	
Potassium	30 (25)	
Zinc sulphate	10 (-)	

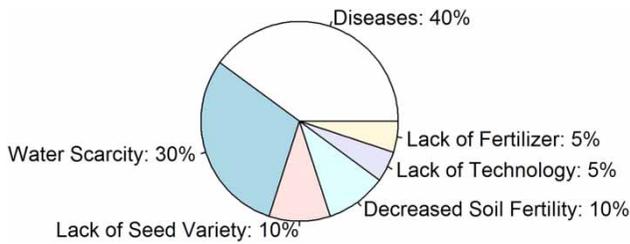


Figure 3 | Major factors affecting the crop growth.

decrease soil fertility (10%), (d) lack of seed varieties (10%), and (e) lack of fertilizer and technology (5% each).

Reported crop yield from the farmers (Table 2) of monsoon rice (4.9 t/ha) is comparable to the findings of MoAC (2010) which stand at 4.5 t/ha. This is also the case for the winter wheat in which responded reported yield (2.5 t/ha) nearly matches with the MoAC (2010) value of 2.69 t/ha. Finally, the phenological periods for monsoon rice and winter wheat are obtained from the questionnaire survey and it is reported that plantation dates for rice and wheat were July 1 and December 15, respectively.

Results from laboratory tests of soil samples

The extracts of laboratory analysis report have been plotted on the textural triangle developed by Gerakis & Baer (2000) which indicated that 80% is classed as 'Silt Loam', while 16% as 'Loam', and remaining 4% as 'Sandy Loam' (Figure 4). Moreover, organic matter content of the soil samples is found to be below 3%. Increased organic matter increases water holding capacity and conductivity (Saxton & Rawls 2006). If organic matter content is

Table 2 | Mean reported yield from respondents

Year (as of 2013)	Rice yield (t/ha)		
	Maximum	Minimum	Average
Before 10 years	11.9	3.0	8.2
Last year	8.9	2.5	5.8
This year	6.9	1.9	4.9
Year (as of 2013)	Wheat yield (t/ha)		
	Maximum	Minimum	Average
Before 10 years	6.7	2.0	3.8
Last year	4.0	1.3	2.5
This year	4.0	1.0	2.5

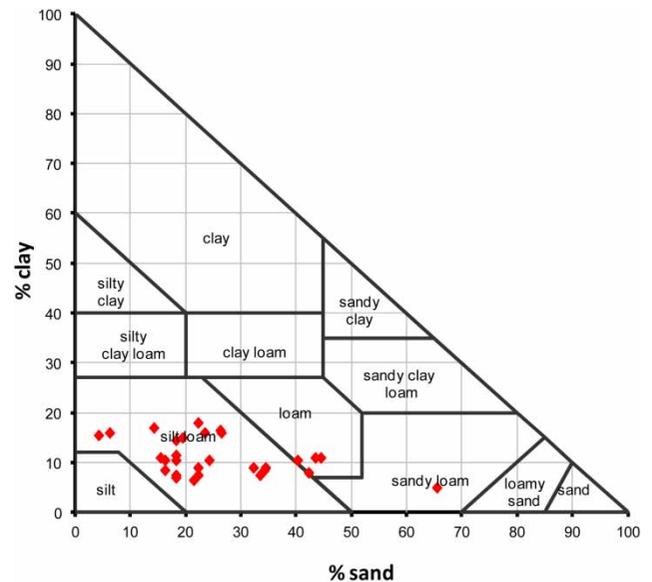


Figure 4 | Textural triangle of collected soil samples.

increased from 0.5 to 3%, the TAW would double (Hudson 1994).

Model results

ETo-calculator results

ETo calculator revealed that the daily ETo have a decreasing trend for the base period (1979–2013) which is contrary to expectation as it is perceived that there would be rise in temperature due to climate change. However, as can be seen in Figure 2, the maximum and minimum temperatures are rather stable in the last decade or so. The decreasing ETo trend could then be due to the higher humidity levels in the atmosphere and decreased amount of solar radiation reaching the Earth's surface. It is well perceived that a small change in solar radiation can bring large amount of change in evapotranspiration (Gad & Gyar 2010).

SPAW model results

Based on the soil physical characteristics as determined using Pedo-transfer functions from soil texture using the SPAW model (Saxton & Rawls 2006), we classified the soil samples into three classes namely S1, S2 and S3. The classification was based on the range of TAW values (refer

to Table 3). Other characteristics of the soil are presented in the Table 3. Spatial distribution of soil samples is presented in Figure 1. It is clear that S3 was the most dominant type in the study area.

AquaCrop model results – model calibration

The calibration results of monsoon rice and winter wheat yield, for soil type S1 are shown in Figures 5 and 6, respectively. As can be seen, only three data points (of the observed

yield) are available, and the simulated yield falls into the range of yield as reported (by the respondents) in the questionnaire survey. However, it should be noted that availability of continuous yearly crop yield data would better reflect the accuracy of model calibration. This limited us to check the accuracy of the model calibration using well established goodness-of-fit statistics such as bias, coefficient of correlation, etc. We found that the provision of a 100% dose of fertilizer as recommended by NRFD and RF condition better matched the yield of latest data (the year of 2013) for both crops, which was somehow expected as most of the farmers (80%, details in ‘Results from social survey’ section) depend on the rainfall occurrence for sowing and plantation, and in later stages of crop development too.

It is clear that monsoon rice yield does not seem to be too sensitive to the total rainfall during crop season. While large variation (600–1,395 mm) in the rainfall is evident,

Table 3 | Classification of collected soil samples

Type	Total soil sample	TAW (mean) mm	SAT (mean) vol %	FC (mean) vol %	WP (mean) vol %
S1	4	100 to 140	42	22	8
S2	9	150 to 180	43	28	11
S3	17	190 to 220	43	31	11

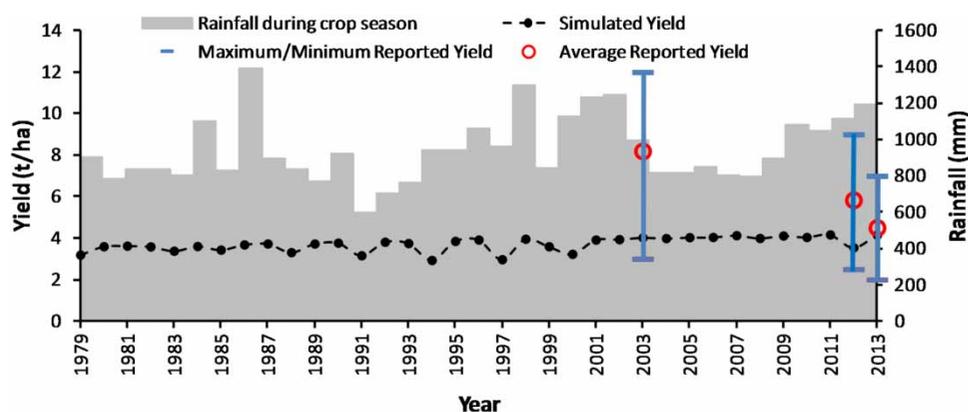


Figure 5 | AquaCrop model calibration results for monsoon rice (soil type S1).

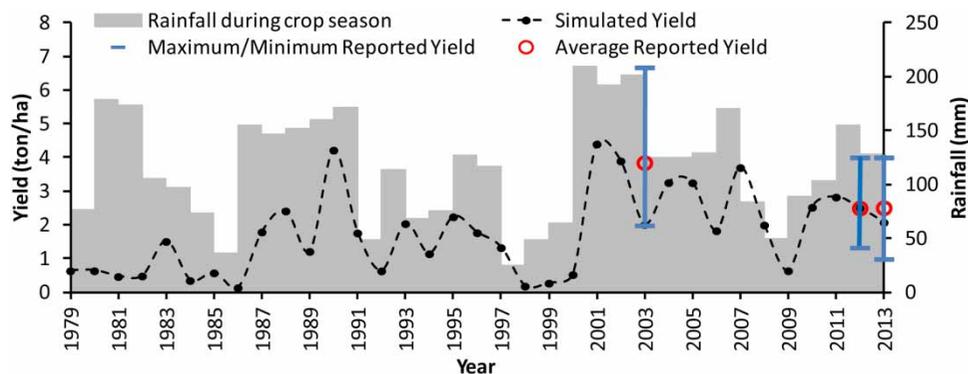


Figure 6 | AquaCrop model calibration results for winter wheat (soil type S1).

the variation in the monsoon rice yield (2.9–4.2 t/ha) is suppressed (Figure 5). The coefficient of correlation (r^2) between them is thus very low (0.04). However, winter wheat yield is very sensitive to total rainfall occurring during crop season (Figure 6). Large variation in rainfall (25–210 mm) is also reflected in large variation in the yield (0.1–4.4 t/ha) with higher r^2 value of 0.37 between them. It therefore implies that RF irrigation can be practiced for monsoon rice while winter wheat needs irrigation infrastructure to ensure timely irrigation and better yield.

Although the calibration result for soil type S1 is presented in Figure 5 (for monsoon rice) and Figure 6 (for winter wheat), the yield scenario for each soil type is shown in Figure 7. As can be seen, the yield on type S3 is the highest and has the lowest variation in terms of maximum and minimum yields, which are mainly due to the higher TAW retaining capacity of S3 (see Table 3). Higher TAW means that the soil can hold more moisture in a prolonged no-rain case.

The monsoon rice yield in different fertilizer and water management scenarios is presented in Table 4. As can be seen, in the RF case, increment in fertilizer application from 0% to 150% of the NTFD resulted in a significant increment in the yield (up to 65%), and the result for the irrigated (FI) case is even higher (up to 74%). The net contribution of irrigation in the yield increment is below 4%. This implies that increment in fertilizer application should be practiced while the provision of even full irrigation would barely be beneficial. It might also be due to the fact that rainfall is enough during the crop growing period, and the development of an irrigation system might not be economically viable for rice anyway. These findings are consistent with the findings of Shrestha *et al.* (2013c) for the southern plain region (Terai) of Nepal.

The same for the winter wheat (Table 5) illustrated a rather different picture. Winter wheat yield could substantially be increased (up to 110%) by providing optimal fertilizer dose, and the contribution of irrigation is also

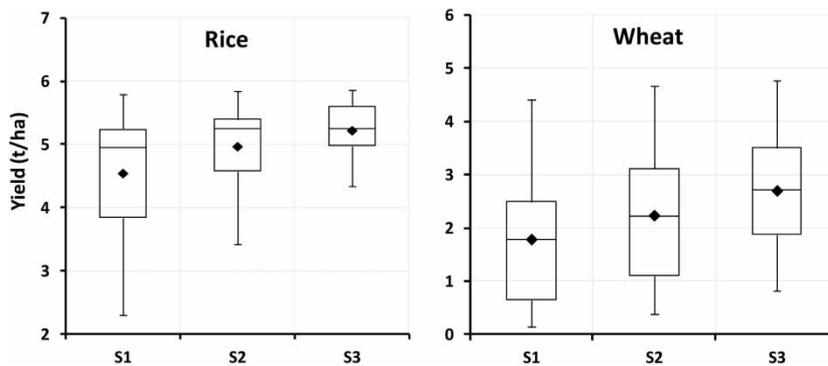


Figure 7 | AquaCrop simulated monsoon rice (left) and winter wheat (right) yield in the base period (1979–2013) for different soil types (S1, S2 and S3).

Table 4 | Contribution of fertilizer and/or irrigation on monsoon rice yield

Fertilizer application dose	RF		Full irrigation (FI)		
	Yield t/ha	Increase by fertilizer %	Yield t/ha	Increase by fertilizer %	Increase by irrigation %
150% of NTFD	5.23	65	5.44	74	4
100% of NTFD	4.35	38	4.41	41	1
50% of NTFD	3.86	22	3.89	23	0.5
0% of NTFD	3.16	–	3.17	–	0.3

AquaCrop simulation results in base period (1979–2013) for soil type S1.
NTFD: National Recommended Fertilizer Dose.

Table 5 | Contribution of fertilizer and/or irrigation on winter wheat yield increment

Fertilizer application dose	RF		Full irrigation (FI)			Deficit irrigation (D1)			Deficit irrigation (D2)		
	Yield t/ha	Increase by fertilizer %	Yield t/ha	Increase by fertilizer %	Increase by irrigation %	Yield t/ha	Increase by fertilizer %	Increase by irrigation %	Yield t/ha	Increase by fertilizer %	Increase by irrigation %
150% of NRFD	2.71	39	4.62	110	71	3.67	77	36	4.13	92	53
100% of NRFD	2.49	28	4	82	61	3.31	60	33	3.65	70	46
50% of NRFD	2.34	20	3.03	38	30	2.7	30	16	2.88	34	23
0% of NRFD	1.94	–	2.2	–	13	2.07	–	7	2.15	–	11

AquaCrop simulation results in base period (1979–2013) for soil type S3.
NRFD: National Recommended Fertilizer Dose.

substantial (up to 71%), unlike that observed in the case of monsoon rice (only up to 4%). Yield response indicated that the increment from the increased fertilizer dose would further be enhanced in the case of FI rather than RF and deficit irrigation (D1, D2). While it is evident that the yield was highest with full irrigation, the yield at deficit irrigation schemes (D1 and D2) would not be too low, especially for the D2 case. Hence, proper deficit irrigation schemes could be the option for the winter wheat along with optimal fertilizer application in order to increase the yield.

AquaCrop – future crop yield in climate change scenario

For all the fertilizer and water management scenarios, model simulation showed two contrasting results when different future (2030–2060) climatic data (HadCM3Q0 and ECHAM5) were forced. For instance, in calibrated conditions (fertilizer: 100% of the NRFD, and RF), the

HadCM3Q0 based simulation showed a marked drop (–63.78%, see Table 6) in monsoon rice yield in future period (2030–2060) as compared to the base period (1979–2013) while the ECHAM5 based simulation showed +20.5% increment (see Table 6). Such significant differences in the yield when using two different climate projection data would surely have implications for policy makers. It should however be noted that different results when using different climatic data sets have been widely reported in the literature. McSweeney & Jones (2010) related such uncertainties to differences in the climate model formulation and the adopted downscaling techniques. Lately, researchers have used Mean Model Ensemble (MME) as future climate data in simulation models (McSweeney & Jones 2010) which can be perceived as balancing the extremes of the climate models. Some researchers (e.g. Prudhomme 2006) thus have warned of ‘misleading conclusions’ derived from different climate change projection models.

Table 6 | Summer rice yield (mean) response in future (2030–2060) relative to baseline period (1979–2014) for both HadCM3Q0 and ECHAM5 forcings

Fertilizer application dose	RF		Full irrigation (FI)			
	Base period yield t/ha	Yield change in future		Base period yield t/ha	Yield change in future	
		HadCM3Q0 %	ECHAM5 %		HadCM3Q0 %	ECHAM5 %
150% of NRFD	5.23	–65.97	24.86	5.44	–36.03	20.04
100% of NRFD	4.39	–63.78	20.50	4.41	–35.60	19.95
50% of NRFD	3.89	–62.21	19.28	3.86	–35.49	19.69
0% of NRFD	3.17	–57.41	17.98	3.12	–34.94	19.55

The HadCM3Q0 based simulation results (drop in summer rice yield) are in line with the findings of: (a) Karn (2014) who reported about 4% drop in rice yield, based on the analysis made on 20 districts of Nepal; (b) Lal (2007) who reported drop of 4–10% for the South Asia; and (c) Palazzoli *et al.* (2015) who found a wide range (–17% to +12%) when using different climate projections, in Indrawoti river basin of central Nepal. While other studies (e.g., Joshi *et al.* 2011; Bhatt *et al.* 2014; Shrestha *et al.* 2014) reported the opposite. As can be seen in Figure 8, the yield would even drop to near zero level. The yield improved when full irrigation was introduced but is still lower than current yield. Unlike that observed in the base period (see Table 4), increasing fertilizer application did not improve the yield in future. These findings (significant increment from the provision of full irrigation and negligible contribution from increasing fertilizer dose) are consistent with

the findings of Acharya & Bhatta (2013) who analyzed the climate change impact in agricultural gross domestic product of Nepal. Moreover, results showed that there exists greater uncertainty in future crop yield as indicated by wider error bars of the box plots as compared to that of current case. As expected, the width or variation in box plots are less in the FI case than that in the RF case which is apparently due to lower water stress on the crop. Such a significant decrease (–36%, for highest fertilizer application case –150% NTFD) even for full irrigation (see Table 6) would mean that temperature stress is the main factor behind such a decrease.

In contrast, the ECHAM5 based simulation showed that the crop yield would increase in future. This finding is in line with the results of Shrestha *et al.* (2014) in Myanmar; Bhatt *et al.* (2014) in Koshi river basin, Nepal; and Joshi *et al.* (2011) across Nepal. For all cases (RF and FI,

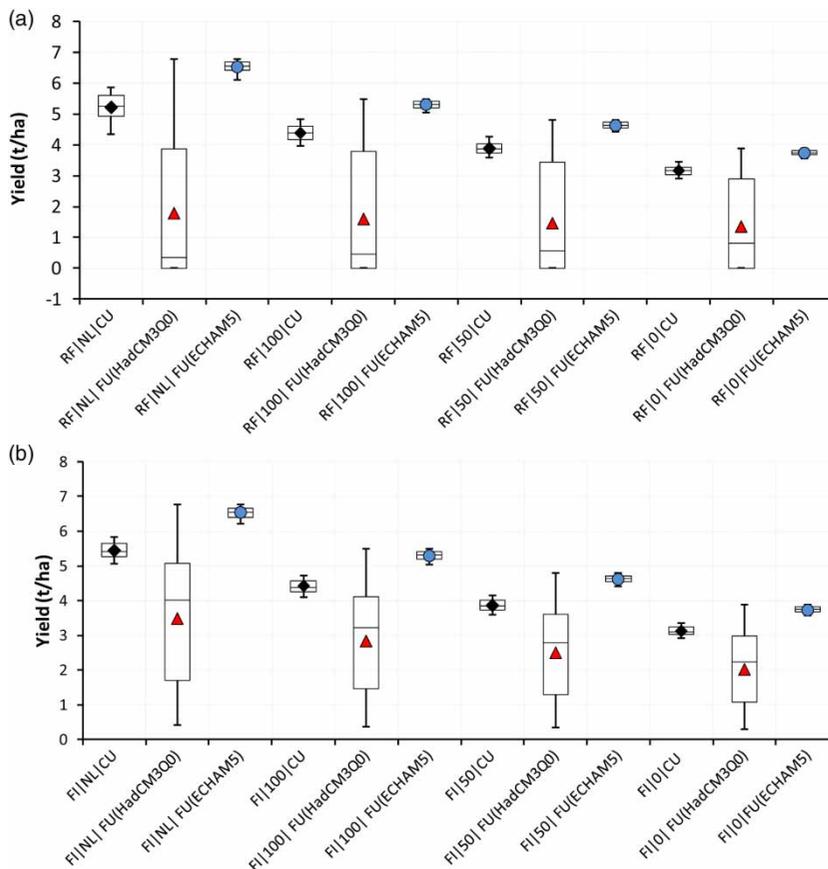


Figure 8 | AquaCrop simulated monsoon rice yield represented as box plots for (a) rainfed (RF), (b) full irrigation (FI). Mean values are shown as black diamond for base/current (CU), and red triangle for future (FU) based on HadCM3Q0 forcing and blue circle based on ECHAM5 forcing. NL, 100, 50, 0 represents fertilizer application scenario as Non-Limiting, 100%, 50% and 0% as per National Recommended Fertilizer Dose (NRFD), respectively.

and all fertilizer application conditions), the ECHMA5 based simulation showed higher yield than current yield. Furthermore, there exists less variation, as indicated by narrower box plots, in the yield which indicates that there would be sufficient rainfall in the monsoon rice growing season, should the ECHAM5 projection prevail in future.

The future simulation results for winter wheat showed different results than that observed for summer rice (Figure 9). The HadCM3Q0 based future simulation showed increment in winter wheat yield in all water management and fertilizer application scenarios which indicates that rainfall and temperature during the winter wheat growing season would be favorable. The ECHAM5 based future simulation however showed increment in certain scenarios and drop in others. In improved water management scenarios (e.g., full irrigation, D1), the future yield is always expected to be higher than current yield (see Figure 9(b) and 9(c), and Table 7). The HadCM3Q0 based simulation results also showed that even deficit irrigation schemes (D1 and D2) would result in better yields (see Figure 9(c) and 9(d), and Table 7). The ECHAM5 based simulation results however showed that the yield would decrease (Table 7) especially in D2 case.

While it is not clear if the monsoon rice yield would increase or decrease in future as both future climate data set indicated contrasting result, it is rather clear that the yield of winter wheat can easily be stabilized or even increased adopting proper water management scenarios (FI or D1). Such significant uncertainty in future yield of monsoon rice is indeed a dilemma for policy makes, hence, an effort was made in investigating what caused such a drastic decrease in monsoon rice yield when forcing the HadCM3Q0 projection.

It was found that significant temperature stress (consequently higher evapotranspiration and higher the demand of irrigation water) would be the main reason behind the sharp decrease in yield if HadCM3Q0 projection prevail in future (see Figure 10, left). During the base period the temperature stress is very low (almost near zero) and variation of temperature stress is also very low (as indicated by narrower box plots). In contrast, the HadCM3Q0 based projected would lead to rather significant temperature stress, ranging from nearly 40% to 10% (Figure 10, left). Extreme

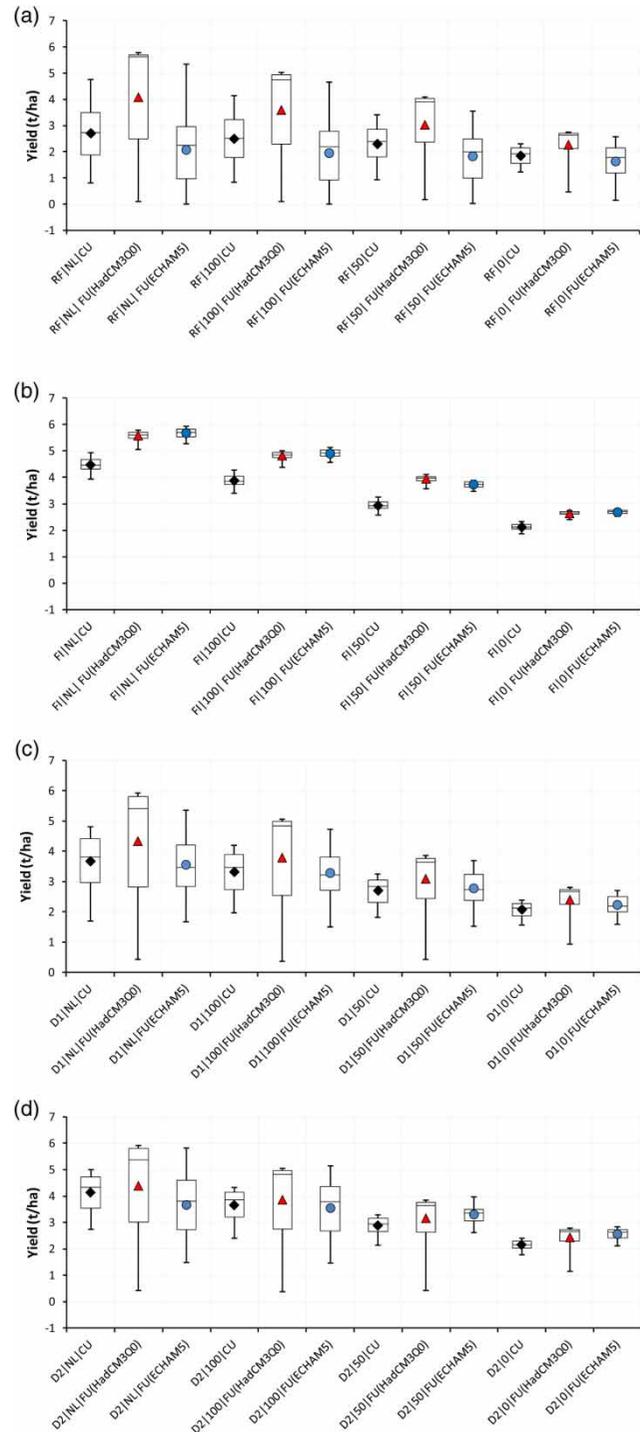


Figure 9 | AquaCrop simulated winter wheat yield represented as box plots for (a) rainfed (RF), (b) full irrigation (FI), (c) deficit irrigation scheme 1 (D1), (d) deficit irrigation scheme 2 (D2). Mean values are shown as black diamond for base/current (CU), and red triangle for future (FU) based on HadCM3Q0 forcing and as blue circle based on ECHAM5 forcing. NL, 100, 50, 0 represents fertilizer application scenario as Non-Limiting, 100%, 50% and 0% as per National Recommended Fertilizer Dose (NRFD), respectively.

Table 7 | Winter wheat yield (mean) response in future (2030–2060) relative to baseline period (1979–2014) for both HadCM3Q0 and ECHAM5 forcings

Fertilizer application dose	RF	Full irrigation (FI)				Deficit irrigation 1 (D1)				Deficit irrigation 2 (D2)			
		Yield change in future		Base period		Yield change in future		Base period		Yield change in future		Base period	
		HadCM3Q0 %	ECHAM5 %	yield t/ha	Yield change in future %	HadCM3Q0 %	ECHAM5 %	yield t/ha	Yield change in future %	HadCM3Q0 %	ECHAM5 %	yield t/ha	Yield change in future %
150% of NRFD	2.7	28.89	-22.96	4.62	23.81	22.51	3.67	18.26	2.18	4.13	6.05	-11.14	
100% of NRFD	2.49	26.10	-22.09	4	23.75	22.50	3.31	14.50	2.72	3.65	5.48	-3.29	
50% of NRFD	2.5	7.39	-20.43	3.03	23.76	22.77	2.7	14.44	2.59	2.88	9.38	8.33	
0% of NRFD	1.84	4.89	-11.96	2.2	23.64	22.27	2.07	15.46	7.25	2.15	13.49	13.02	

temperature indeed has a negative effect on photosynthesis, primary and secondary metabolism, and stability of various proteins, membranes and cytoskeleton structures, resulting in low yield. The effect is more pronounced in the reproductive stage. Furthermore, water stress due to low rainfall and high evapotranspiration demand also contributed to the low yield. When a plant does not get a sufficient amount of water for growth, then yield will certainly decrease. Both extreme high and low temperatures affect the crop progress significantly. According to Shrestha (2014), crop does not progress well at temperature below 8 °C and above 30 °C.

Furthermore, there would be rather unfavorable rainfall occurrence and distribution in monsoon rice crop growing season (see Figure 10, right). The cumulative rainfall (mean) for the season would be less than 500 mm if HadCM3Q0 projection prevails in future while the ECHAM5 projection indicates comparable cumulative rainfall with that occurring in the base period.

To further analyze the case, for a purposively selected year (2044), it was found that temperature seems to drop below 8 °C (even reaching below freezing) for a prolonged time of almost 3 months if HadCM3Q0 projection prevail in future (Figure 11, top right). Similarly, there would be very limited rainfall during the rice growing season (Figure 11, top left). Rather, the rainfall peaks seem to be shifted to earlier months with the highest during mid-March. This implies that rice's plantation date need to be shifted so as to benefit the ample rain. Furthermore, the minimum temperature also seems favorable for shifting of the plantation date. This issue (shifting crop plantation month) is further investigated, results of which have been presented in the next section. If ECHAM5 projection prevails, it is clear from the plots that there would be rather favorable distribution of rainfall (Figure 11, bottom left) and temperature barely drops below 8 °C (Figure 11, bottom right) meaning that there would be minimal water and temperature stress.

AquaCrop – shifting crop plantation season to stabilize crop yield

The previous simulation results, in the case of monsoon rice, indicated a marked decrease in yield in all possible management scenarios, should HadCM3Q0 projection prevail in future. Moreover, rainfall and temperature seem to favor

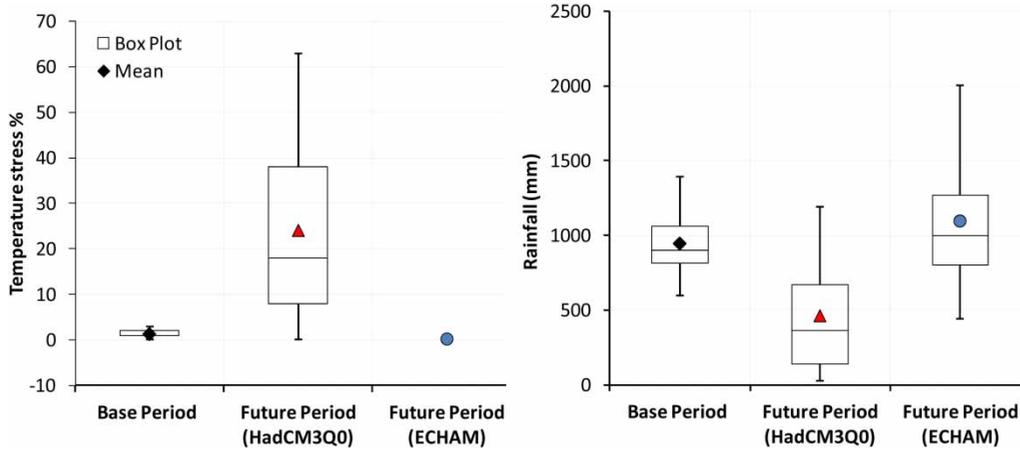


Figure 10 | Temperature stress (left) during the crop growing season for monsoon rice for base and future period. Also shown is the rainfall occurrence during season (right).

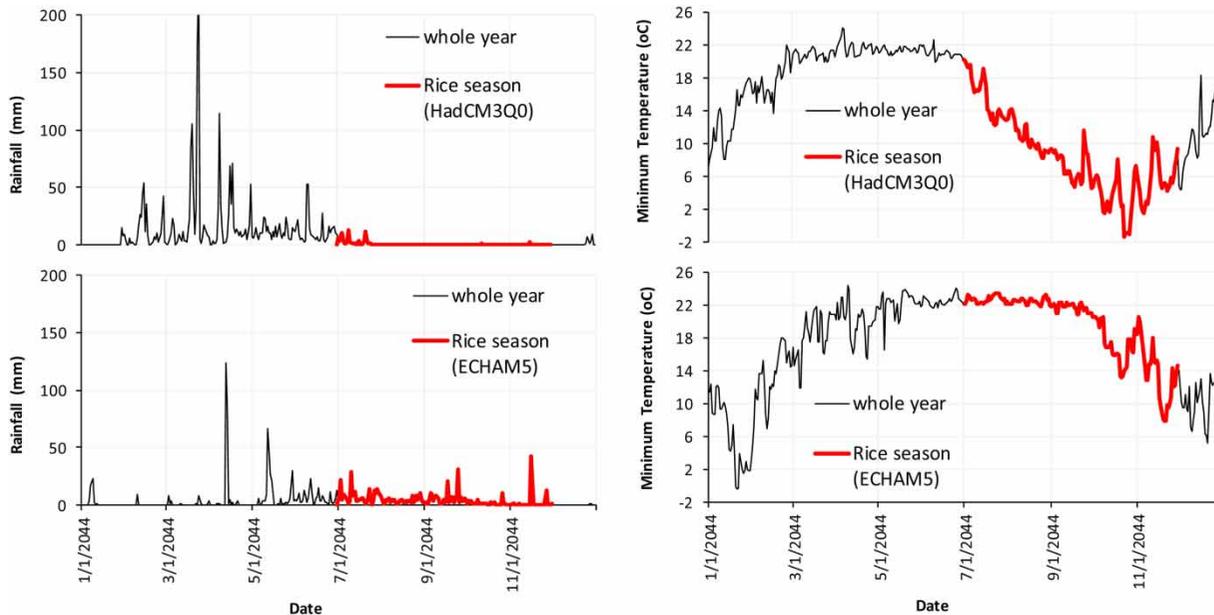


Figure 11 | Rainfall distribution pattern for the year of 2044 (left) and minimum temperature pattern (right).

an earlier plantation date (mid-March, see Figure 11). As an adaptation measure for the climate change impact, and in order to stabilize the monsoon rice yield, crop plantation months were arbitrarily shifted and simulations with both water management scenarios, RF and FI, are carried out. It has to be noted that the worst future climatic scenario (HadCM3Q0 projection) has been considered here, as simulation based on ECHAM5 projection showed increment in monsoon rice yield.

Simulations showed that the March plantation of monsoon rice would result in the maximum yield for both RF

and FI conditions under optimal fertilizer application dose (Figure 12). Even under FI conditions, the tradition plantation date (July) of monsoon rice would give almost the lowest yield, mainly due to temperature stress as minimum temperature in subsequent crop growing months tends to reach below 8 °C.

AquaCrop – net irrigation water requirement

The simulation result of net irrigation water requirement (I_{net}) also indicates the severe water stress that the monsoon

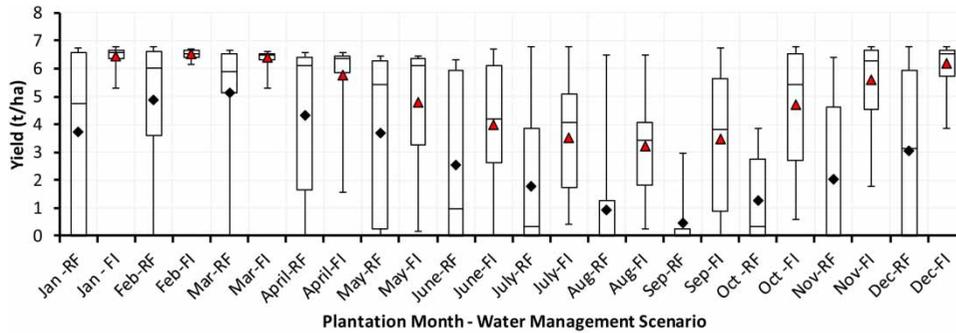


Figure 12 | Monsoon rice yield in rainfed (RF) condition (black diamond) and full irrigation (FI) condition (red triangle) in each months of future (HadCM3Q0 based) period under Non-Limiting (NL) fertilizer application. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wcc.2016.153>.

rice would face (Figure 13, left), should HadCM3Q0 projection prevail in future. The I_{net} (155 mm) during the base period increased significantly to 317 mm which is comparable to I_{net} value reported by Shrestha *et al.* (2013a). Should ECHAM5 projection prevail in future, the favorable rainfall distribution during rice growing season has been reflected in a very low value (<60 mm) of I_{net} . With this hindsight, possible adaptation measures might be the provision of irrigation facility and shifting of monsoon rice plantation date.

On the other hand, the main reasons for a rather stable winter wheat yield (based on HadCM3Q0 projection) are due to favorable rainfall distribution and lessened temperature stress (Figure 10, left). However, the wider range of the error bars of the box plot of I_{net} , meaning higher variability, is of concern to policy makers. Furthermore, the I_{net} based on ECHAM5 projection is higher than base period indicating

that less rainfall is expected during winter wheat's growing season which is also evident in Figure 11 (bottom left).

CONCLUSIONS

An assessment of climate change impact on irrigation water requirement and crop yield of two widely used cereal crops in Bhaktapur district, Nepal, was made with the help of social and analytical (using various models) techniques. Questionnaire survey with 30 farmers, selected using snowball sampling technique, was carried out to gain insights on the crop, water and fertilizer management practices, and harvested yield. Moreover, soil samples from the croplands of the selected farmers were taken and later analyzed in a laboratory to determine texture composition and organic matter content. SPAW tool was used to determine physical

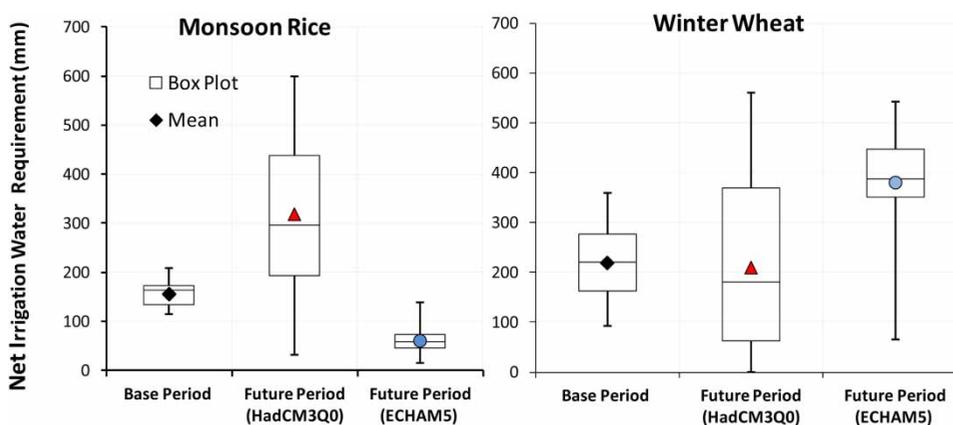


Figure 13 | Net irrigation water requirement in base (black diamond) and in future (HadCM3Q0 – red triangle and ECHAM5 – blue circle) for monsoon rice (left) and winter wheat (right). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wcc.2016.153>.

characteristics of the samples, and the ETo calculator was used to estimate daily potential evapotranspiration series. To study the crop-yield response on forced climatic, crop, soil, and management data, a yield simulation model namely, the AquaCrop model was calibrated. To realize the possible impacts of climate change 30 years of future climate data (2030–2060), as simulated by Providing Regional Climates for Impacts Studies (PRECIS) based on regional circulation model simulation of HadCM3Q0 and ECHAM5 for A1B scenario, were forced to the calibrated AquaCrop model. Finally, some realistic water and fertility management scenarios for the selected crops were formulated and simulated so as to explore ways of stabilizing the crop yield.

Laboratory and SPAW analysis confirmed silt loam as being the most dominant soil type in the study area. The AquaCrop model was able to simulate crop yield with reasonable accuracy. Future (2030–2060) crop yield simulations indicated decreased yield (based on HadCM3Q0 projection) and increased yield (based on ECHAM5 projection) of monsoon rice and stable yield of winter wheat as compared to base period (1979–2014) yield. Simulation results for the management strategies indicated that the monsoon rice and winter wheat yields were mainly constrained by water scarcity and fertility stress, and that such a situation can be overcome with improved fertilizer application and proper irrigation management. Moreover, winter wheat yields in the dry season could easily be stabilized and could even be increased with proper deficit irrigation strategies. Results also indicated that an increase in fertilizer application was more effective in fully irrigated conditions than in the RF condition. Analysis relating to shifting of crop plantation date showed a marked increase in the crop yield of the monsoon rice in the future period. This study therefore recommends shifting of crop plantation date, temperature resilient crop genotype (to overcome temperature stress), and proper water and fertilizer management to stabilize the crop yield.

ACKNOWLEDGEMENTS

Ms L. Shrestha received financial support from Center of Research for Environment, Energy and Water (CREEW),

Nepal, to conduct this study. The authors are very grateful for Dr Nirman Shrestha and Mr Pabitra Gurung for providing valuable suggestions.

REFERENCES

- Acharya, S. K. & Bhatta, G. R. 2013 *Impact of Climate Change on Agricultural Growth in Nepal*. NRB working paper series, NRB-WP-15. Nepal Rastra Bank, Nepal.
- Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Bhatt, D., Maskey, S., Babel, M., Uhlenbrook, S. & Prasad, K. C. 2014 *Climate trends and impacts on crop production in the Koshi River basin of Nepal*. *Regional Environmental Change* **14**, 1291–1301.
- FAO 2011 *Climate Change, Water and Food Security*. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Gad, H. E. & Gyar, S. M. 2010 Effect of solar radiation on the crops evapotranspiration in Egypt. In: *14th International Water Technology Conference*, Cairo, Egypt, 21–23 March.
- Geerts, S. & Raes, D. 2009 *Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas*. *Agricultural Water Management* **96**, 1275–1284.
- Geerts, S., Raes, D., García, M., Vacher, J., Mamani, R., Mendoza, J., Huanca, R., Morales, B., Miranda, R., Cusicanqui, J. & Taboada, C. 2008 *Introducing deficit irrigation to stabilize yields of quinoa (Chenopodium quinoa Willd.)*. *European Journal of Agronomy* **28**, 427–436.
- Geerts, S., Raes, D. & Garcia, M. 2010 *Using AquaCrop to derive deficit irrigation schedules*. *Agricultural Water Management* **98**, 213–216.
- Gerakis, A. & Baer, B. 2000 *Computer program for soil textural classification*. *Soil Science Society of America Journal* **63**, 807–808.
- Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B. & Wood, R. A. 2000 *The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments*. *Climate Dynamics* **16**, 147–168.
- Hudson, B. D. 1994 *Soil organic matter and available water capacity*. *Journal of Soil and Water Conservation* **49**, 180–194.
- IFPRI 2009 *Climate Change Impact on Agriculture and Costs of Adaptation*. Food policy report of International Food Policy Research Institute. International Food Policy Research Institute, Washington, DC.
- Iizumi, T. & Ramankutty, N. 2015 *How do weather and climate influence cropping area and intensity?* *Global Food Security* **4**, 46–50.
- IPCC 2000 *IPCC Special Report Emissions Scenarios: Summary for Policymakers. A Special Report of IPCC Working Group III*. IPCC, Geneva, Switzerland.

- IPCC 2014 *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.
- Jones, R. G., Noguera, M., Hassell, D. C., Hudson, D., Wilson, S. S., Jenkins, G. J. & Mitchell, J. F. B. 2004 *Generating High Resolution Climate Change Scenarios Using PRECIS*. Met. Office, Hadley Centre, Exeter.
- Joshi, N. P., Maharjan, K. L. & Luni, P. 2011 Effect of climate variables on yield of major food-crops in Nepal – A time series analysis. *Journal of Contemporary India Studies: Space and Society* **1**, 19–26.
- Karn, P. K. 2014 *The Impact of Climate Change on Rice Production in Nepal*. SANDEE working paper No. 85-14.
- Lal, M. 2007 *Implications of Climate Change on Agricultural Productivity and Food Security in South Asia. Key Vulnerable Regions and Climate Change – Identifying Thresholds for Impacts and Adaptation in Relation to Article 2 of the UNFCCC*. Springer, Dordrecht, The Netherlands.
- Malla, G. 2008 Climate change and its impact on Nepalese agriculture. *The Journal of Agriculture and Environment* **9**, 62–71.
- Maximay, S. 2014 The Caribbean's response to climate change impacts. In: *Impacts of Climate Change on Food Security in Small Island Developing States* (W. Ganpat & W.-A. P. Isaac, eds). pp. 33–66.
- McSweeney, C. & Jones, R. 2010 *Selecting Members of the 'QUMP' Perturbed-Physics Ensemble for use with PRECIS*. Met. Office, Hadley Centre, UK.
- MoAC 2010 *Statistical Information of Nepalese Agriculture 2009/10*. Ministry of Agriculture and Co-operatives (MoAC), Kathmandu, Nepal.
- NCDP 2014 *Nepal Climate Data Portal User Manual (V 0.6)*. [Online] Asian Disaster Preparedness Center, Department of Hydrology and Meteorology, Ministry of Environment (Government of Nepal), Asian Development Bank (accessed 29 September 2014).
- Palazzoli, I., Maskey, S., Uhlenbrook, S., Nana, E. & Bocchiola, D. 2015 *Impact of prospective climate change on water resources and crop yields in the Indrawati basin, Nepal*. *Agricultural Systems* **133**, 143–157.
- Poudel, J. P., Tandon, H. & Bhattarai, A. 2012 *District Development Profile of Nepal*. Mega Publication and Research Center, Kathmandu, Nepal.
- Prudhomme, C. 2006 GCM and downscaling uncertainty in modelling of current river flow: why is it important for future impacts? In: *Climate Variability and Change – Hydrological Impacts. Proceedings of the Fifth FRIEND World Conference*, Havana, Cuba, November 2006.
- Raes, D., Steduto, P., Hsiao, T. C. & Fereres, E. 2012 AquaCrop version 4.0 – reference manual. [Online] Available at: <http://www.fao.org/nr/water/docs/AquaCropV40Chapter2.pdf> (accessed 13 December 2014).
- Saxton, K. E. & Rawls, W. J. 2006 *Soil water characteristic estimates by texture and organic matter for hydrologic solutions*. *Soil Science Society of America Journal* **70**, 1578–1596.
- Saxton, K., Willey, P. H. & Rawls, W. J. 2006 Field and pond hydrologic analyses with the SPAW Model. In: *An ASABE Meeting Presentation. American Society of Agriculture and Biological Engineer Portland Convention Center*, Portland, OR.
- Shrestha, N. 2014 Improving cereal production in Terai region of Nepal: Assessment of field management strategies through the model based approach. Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Bioscience Engineering, KU Leuven, Science, Engineering & Technology, Kathmandu, Nepal.
- Shrestha, S., Gyawali, B. & Bhattarai, U. 2013a *Impacts of climate change on irrigation water requirements for rice-wheat cultivation in Bagmati River basin, Nepal*. *Journal of Water and Climate Change* **4**, 422–439.
- Shrestha, A., Karki, K., Shukla, A. & Sada, R. 2013b *Groundwater Extraction: Implications on Local Water Security of peri-urban, Kathmandu, Nepal*. Peri Urban Water Security Discussion Paper Series, Paper No. 7, SaciWATER.
- Shrestha, N., Raes, D., Vanuytrecht, E. & Sah, S. K. 2013c *Cereal yield stabilization in Terai (Nepal) by water and soil fertility management modelling*. *Agricultural Water Management* **122**, 53–62.
- Shrestha, S., Thin, N. M. M. & Deb, P. 2014 *Assessment of climate change impacts on irrigation water requirement and rice yield for Ngamoeyeik Irrigation Project in Myanmar*. *Journal of Water and Climate Change* **5**, 427–442.

First received 10 December 2015; accepted in revised form 3 September 2016. Available online 27 October 2016