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Assessing crop production in rainfed land with and without rainwater harvesting system under various precipitation and crop characteristic scenarios

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ABSTRACT: More than 94% of the cropland in sub-Saharan Africa, and about 66% of the cropland in Asia is rainfed. Although crop yields of rainfed cropland are relatively poor, rainfed cropland produces about 70% of the world's food supply. Since rainfed crop production dominates the world's food supply, improving water availability for rainfed cropping system warrant attention. To improve the water availability in rainfed areas, rainwater harvesting system can be a viable option. Water stored in rain water storage structures during a rainy season can help improving water availability in a dry season i.e., stored water can be used to provide supplemental irrigation (*SI*) to crops. The benefits of such system, however, will largely depend on rainfall patterns and crop characteristics. To improve understanding of rainwater harvesting system suitability for increasing crop production, here calculations were made for evaluating the impacts of various rainfall patterns and crop characteristics on crop yields of rainfed areas with and without rainwater harvesting system. Two scenarios: 1) rainfall scenario, which simulates the dry and wet conditions; 2) crop characteristic scenario, which simulates the impacts of crop coefficients on crop yield were simulated. In both the scenarios, crop yields and water uses were estimated with *SI* (i.e., rainwater harvesting system) and without SI (no rainwater harvesting system). Results indicate that the performance of rainwater harvesting system varies considerably with rainfall patterns and crop characteristics. For example, in an average rainfall condition the crop yield of a rainfed land without rainwater harvesting system was 33% of the crop yield of the rainfed land with rainwater harvesting system. During dry season, however, when rainfall was 50% lower than the average precipitation, crop yield in without rainwater harvesting system was only 14% of the crop yield of the rainwater harvesting system. Similarly, when crop coefficients were increased by 50%, the crop yield of without rainwater harvesting system was 21% of the crop yield of rainwater harvesting system. The results and approach presented here will help improving rainwater management in rainfed areas for increasing crop production.

KEY WORDS: rainwater harvesting; rainfed agriculture; climate conditions; crop characteristics

1 INTRODUCTION

On-farm reservoir (OFR) systems designed to store rainwater for crop irrigation during the dry season is ancient practice dating back to 4500 B.C. (Li et al, 2000, Gunnell and Anupama, 2003, Cornelis et al., 2012, Boers and Ben-Asher, 1982, Tian et al., 2003) and the relics of these water bodies and such systems are still in use in the rural parts of many developing countries. Preference for large water storage facilities during 19-20th centuries and the predominant use of groundwater for irrigation purposes, however, made them obsolete until recently. Considering the OFR's importance in recharging local groundwater systems and irrigating crops in rainfed areas, these structures are crucial for rural livelihoods.

Currently agriculture is the largest water consumer in the world, which consumes about 75% of the total water use. The consumed water can be classified as green water (i.e., precipitation water infiltrated into root-zone layer) or blue water (i.e., withdrawal for agriculture minus return flow to river system) (Falkenmark and Rockström, 2006). Approximately 80% of global cropland is rainfed, and these crop lands mainly rely on green water. Rainfed land produces 60-70% of world's food (Rost et. at, 2008, Falkenmark and Rockström, 2006). Existing water consumption trends indicate that increasing water demands for domestic and industrial uses will likely reduce the water availability for agricultural purposes in the future (van der Zaag and Gupta, 2008), therefore, additional water resources will be required to meet the future food demands.

Cropping systems in many semiarid and dry subhumid savannah regions require a water storage capacity of around 200 mm annually (Rockström et al., 2002, 2009). Crops are able to avail approximately 50% of water need from the moisture available in soil profile but crops require an additional 100 mm of water to achieve maximum yield potential (van der Zaag and Gupta, 2008). The OFR system has potential to provide the required water to increase agricultural production in rainfed areas by storing precipitation received during the rainy season with supplemental irrigation (SI) during dry periods.

Use of the OFRs to enhance the green and blue water availability in rainfed areas can help meet growing water demands and provide sustainable global food supplies The use of OFR (i.e., rainwater harvesting system) for SI has been reported extensively (Mialhe et al., 2008, Panigrahi et al, 2001, Gunnell and Anupama, 2003, Palanisami and Meinzen-Dick, 2001, Pandey et al., 2011), however, further advancement is required in developing the tools capable of assessing the OFR suitability and benefit under various climate and crop conditions. A study by Rockström et al. (2009) reported 56% of increase in crop yield using SI in rainfed areas. Many other previous studies (Palanisami and Meinzen-Dick, 2001, Balasubramanian and Selvaraj, 2003,Glendenning et al., 2012, Ghimire and Johnston, 2013) have also reported the profitability of the rainwater harvesting system for small farmers. A recent paper published by Pandey et al (2013) developed a hydro-economic model for predicting the OFR potential for providing supplemental irrigation to crops and its benefits. The benefits of OFR systems in increasing crop yields may largely depend on rainfall patterns and crop characteristics. Therefore, here the hydro-economic model was exploited to evaluate the impacts of rainfall patterns (i.e., climate) and crop characteristics (i.e., crop coefficient) on the profitability of the OFR system. The objective of this study is to assess the impacts of rainfall scenario (i.e., dry and wet seasons) and crop characteristic scenario (i.e., variable crop coefficients) on crop production and water uses of rainfed land with and without rainwater harvesting system.

2 STUDY AREA AND METHODS

The study area (22° 19′ 48.86″ N, 87° 19′ 25.15″ E; elevation 29 m) (Figure 1) has a sub-humid and tropical savannah climate. The mean minimum and maximum air temperatures are 12 ^{0}C and 40 ^{0}C in January and May, respectively. The area receives about 1500 mm mean annual rainfall, about 75% of which is concentrated during the rainy season from June to September. The crops grown in this region are rainfed.

The hydro-economic model used in this study is described elsewhere (Pandey et al., 2013). Water flows of the model are shown in Figure 2. The input data of the model include: latitude of the site; rainfall (mm/day); daily average temperature (^{0}C); daily average relative humidity (%); wind speed (m/s); measured global solar radiation (MJ/m2/day). Land and OFR related required data are: catchment area in m^2, OFR area in m^2 (percentage of the catchment devoted for the OFR construction), and crop land area. The A_{OFR} was set to 13% of the catchment area of 3 ha, and crop land area was 1 ha. A curve number (USDA-SCS, 1972) of 82 was used to estimate runoff from catchment area. Field investigation and field experiments of the OFR system are reported by Pandey et al. (2006).

The climate data used in simulation were obtained from Department of Physics and Meteorology, Indian Institute of Technology, Kharagpur, India; and global solar radiation data were obtained from Solar Radiation Handbook (2008), Solar Energy Center, MNRE, Indian Meteorological Department. For a year simulation, the average climate dataset of the three years (1997, 1998, and 1999) were used. The solar radiation data is the average of 23 years of data (1986 to 2008). The daily solar radiation of these two locations was obtained from monthly solar radiation by fitting polynomial lines ($R^2 = 0.99$).

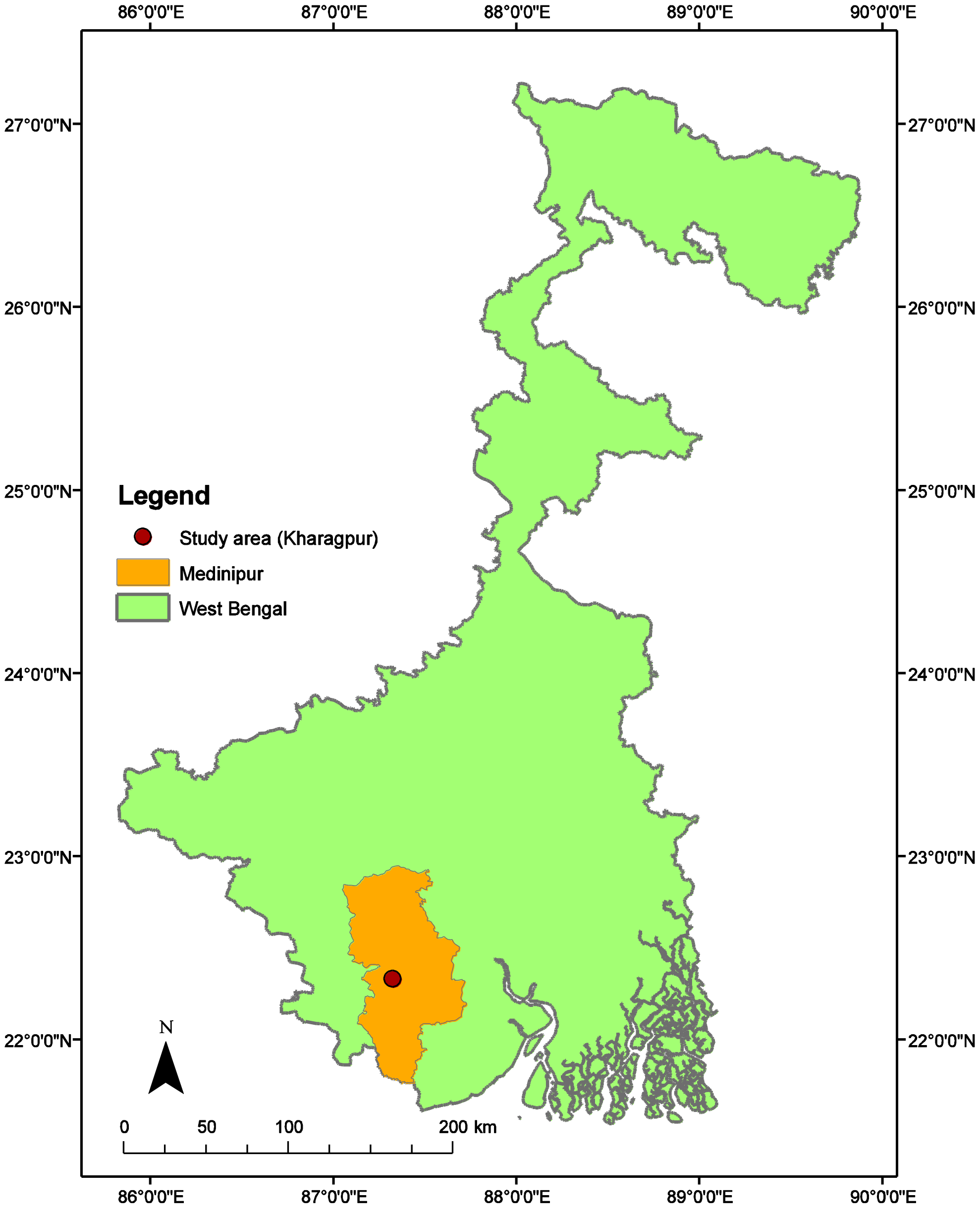


Figure 1 Study area in rainfed area of West Bengal, India.

The model was implemented for a year datasets. Simulation year was divided into two cropping seasons 20-119 Julian days and 165-264 Julian days. Each season period was 100 days with four growth stages: initial; crop development; mid-season and late season. The *Kc* values of a bean crop varied from 0.15 (initial stage) to 0.56 (late season stage) with maximum 1.19 during midseason. ET_c was estimated by multiplying reference evapotranspiration (ET_0) into crop coefficient (*Kc*) (i.e., crop characteristics) using FAO method (Allen et al., 1998). Out of two cropping seasons, the first season (20 – 119 Julian days) requires SI due to unavailability of rainfall (Pandey et al., 2013).

In order to predict crop yields and water uses, the model calculates effective precipitation, soil moisture, OFR water availability, and supplemental irrigation (*SI*) and crop yields (*Yc*). The other estimations were total water use, and overall water use efficiency (*WUE*). The parameters such as runoff, evapotranspiration, evaporation, readily available moisture (*RAM*), Non-readily available moisture (*NRAM*), deep percolations and seepage used in water balance equation were also calculated. The methodologies for parameter estimation and the model inputs are described by Pandey et al. (2013).

The change in soil water of irrigated conditions (i.e., with OFR) was written as:

$$\frac{ds}{dt} = P_{eff} - Q - ET_a - D + SI \qquad (1)$$

The change in soil water in rainfed conditions (i.e., without OFR) was written as:

$$\frac{ds}{dt} = P_{eff} - Q - ET_a - D \qquad (2)$$

The OFR water balance was written as:

$$\frac{dW}{dt} = P + Q - E - S - SI - Spill \qquad (3)$$

where ds/dt is change in soil water (mm/day); dw/dt is change in OFR water (mm/day); $P_{eff,}$ Q, ET_c, E, D, SI, S, *and* $Spill$ are the effective precipitation (daily rainfall minus 2 mm interception loss), runoff, calculated evapotranspiration, evaporation, deep percolation, supplemental irrigation, OFR seepage in (mm/day), and spill from the OFR.

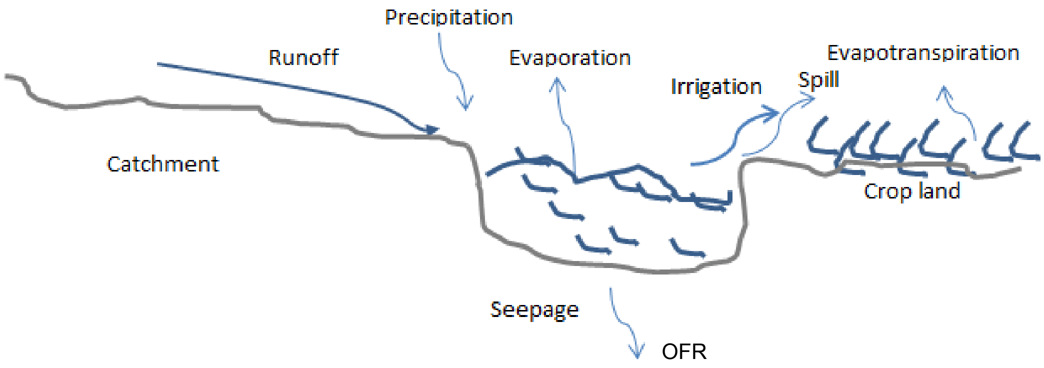


Figure 2 Water flows of the model

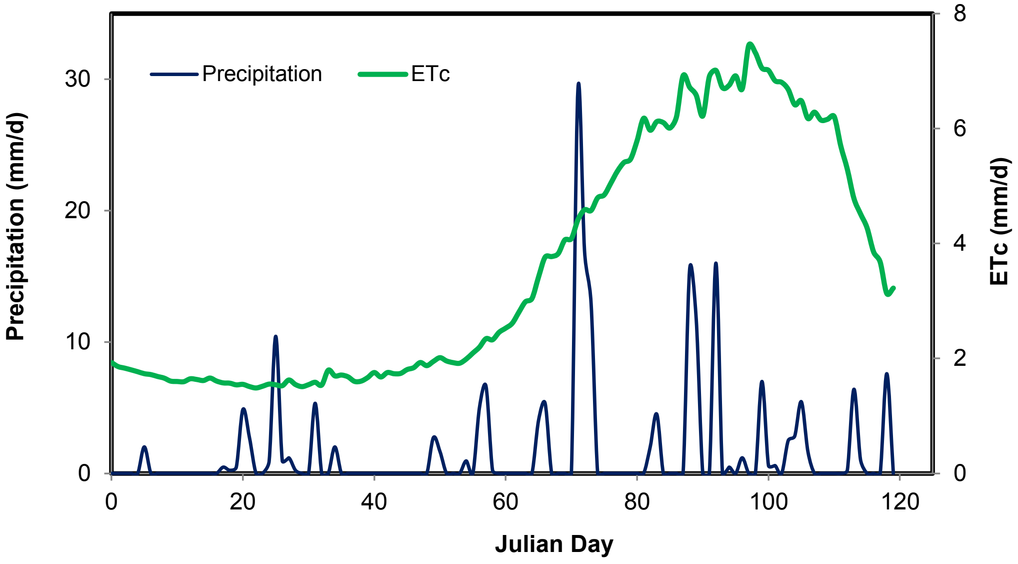
In this study, the focus was to understand how various rainfall patterns and crop characteristics affect crop yields of the rainfed land in the first season (i.e., dry season). Two scenarios were developed: 1) rainfall scenario which simulates crop yields and water uses under dry and wet conditions; 2) crop characteristic scenario, which simulate crop yield and water uses under various crop coefficient conditions. In rainfall scenario, crop yields and water uses were predicted in normal rainfall condition (i.e., average of daily rainfall of 1997, 1998, and 1999), in dry conditions when rainfall was decreased from normal rainfall by 10 – 70%, and wet conditions, when rainfall was increased by 10 – 70%. In crop characteristic scenario, crop yield and water uses were estimated in normal condition (i.e., using the crop coefficient of a bean crop), in decreasing crop coefficient condition (i.e., crop coefficient was decreased from normal by 10 – 50%), and in increasing crop coefficient condition (i.e., crop coefficient was increased from normal by 10 – 50%).

3 RESULTS AND DISCUSSION

3.1 Impacts of changes in precipitation on crop yield

Figure 3(a) shows the average precipitation and calculated evapotranspiration *ETc* for Julian days starting from 20 to 119 (first cropping season). Figure 3(b) shows daily crop coefficient (*Kc*) values for a dry bean crop, which was estimated by interpolating the crop coefficients of four growth stages (i.e., initial, crop development, mid-season, and late season).

(a)



(b)

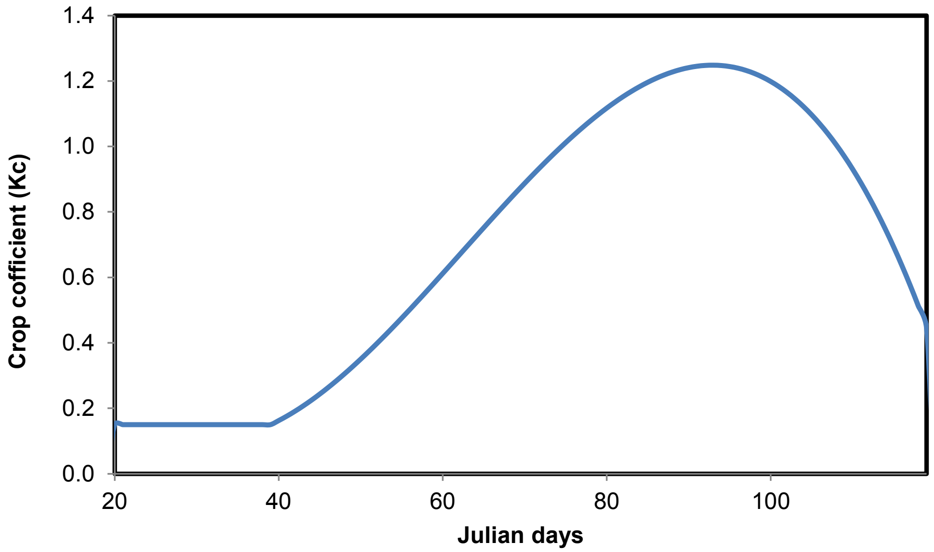
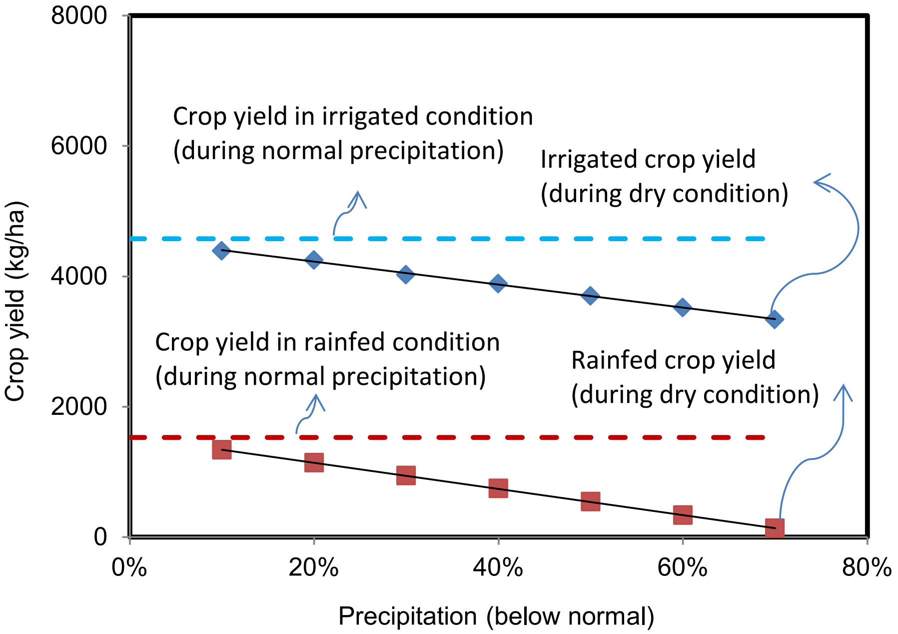


Figure 3 Precipitation, calculated crop evapotranspiration (*ETc*), and crop coefficient (*Kc*): a) precipitation and *ETc*; b) crop coefficient (*Kc*) of a bean crop.

The average of daily *Kc* value was 0.69 (±0.41) with range of 0.15 – 1.25, while the average of daily ET_0 was 4.64 (±1.10) mm/d with range of 2.97 – 6.67 mm/d. The average of daily precipitation shown in Figure 3(a) was 2 (± 4.5) mm/d with range of 0 – 29 mm/d during the cropping season (20 – 119 Julian days). While cumulative precipitation was 202 mm, effective cumulative precipitation was 122 mm.

Figure 4(a) and 4(b) show rainfall scenario analysis indicating the impacts dry and wet rainfall conditions on the crop yields.

(a)



(b)

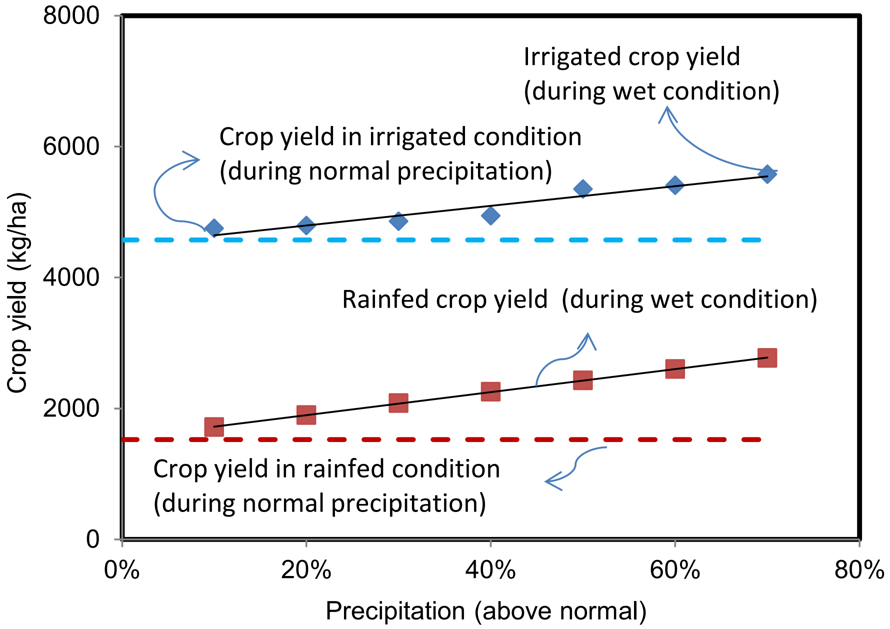


Figure 4a,b Impacts of precipitation on crop yield: a) precipitation was reduced by 10 – 70% from average precipitation shown in Figure 1; b) precipitation was increased by 10 – 70% from average precipitation shown in Figure 1. Corresponding impacts on crop yield is shown in y-axis. Light blue and red dotted line indicate crop yield under irrigated and rainfed conditions, respectively, during average precipitation (i.e., no change in precipitation).

The daily precipitation was reduced by 10 – 70% (Fig. 4(a)). The figure shows crop yields with and without OFR systems (i.e., rainwater harvesting system). During the normal precipitation, the crop yield in irrigated condition (with OFR) was 3 times greater than the crop yield of rainfed condition (without OFR). When precipitation was lowered by 20%, the crop yield in irrigated system was about 3.7 times greater than the crop yield of rainfed condition. However, when precipitation was reduced by 70%, the crop yield of rainfed system was only 4% of the crop yield of the irrigated condition.

To understand how wet conditions potentially will influence crop yields, we increased the precipitation by 10 – 90%, and estimated crop yields. The crop yields under wet condition are shown in Figure 4(b). The blue diamond markers show crop yield in irrigated condition, while red rectangle markers show crop yield under rainfed condition. When the precipitation was increased by 10%, crop yield in irrigated condition was 2.7 times greater than the rainfed crop yield. At 20% greater precipitation, the crop yield of irrigated condition was 2.5 times greater than the crop yield of rainfed condition (without OFR). However, when precipitation was increased by 70%, the crop yield of irrigated condition was only 2 times greater than the rainfed crop yield. Potentially due to increased water availability for both rainfed and irrigated condition at enhanced precipitation conditions.

Figure 4(c) shows rainfed crop yield fraction (i.e., ratio between the crop yield of rainfed and the crop yield of irrigated conditions) under dry and wet conditions. Under normal precipitation, rainfed crop yield was 33% of the irrigated crop yield (shown using dotted red line). Under dry conditions, when precipitation was reduced by 10 – 70%, crop yields in rainfed condition (shown using red rectangle markers) were 0.3 – 0.04 fraction of crop yields in irrigated condition, respectively. However, when precipitation was increased by 10 – 70%, the rainfed crop yield fractions (shown using blue diamond markers) changed from 0.36 to 0.50, respectively.

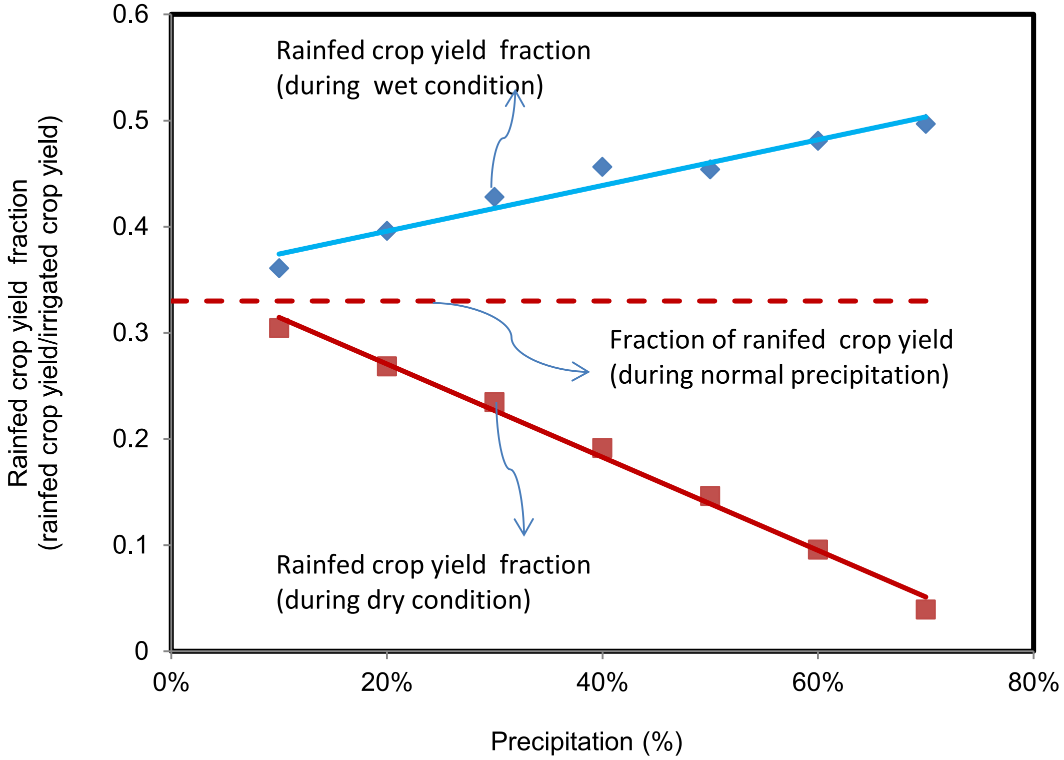


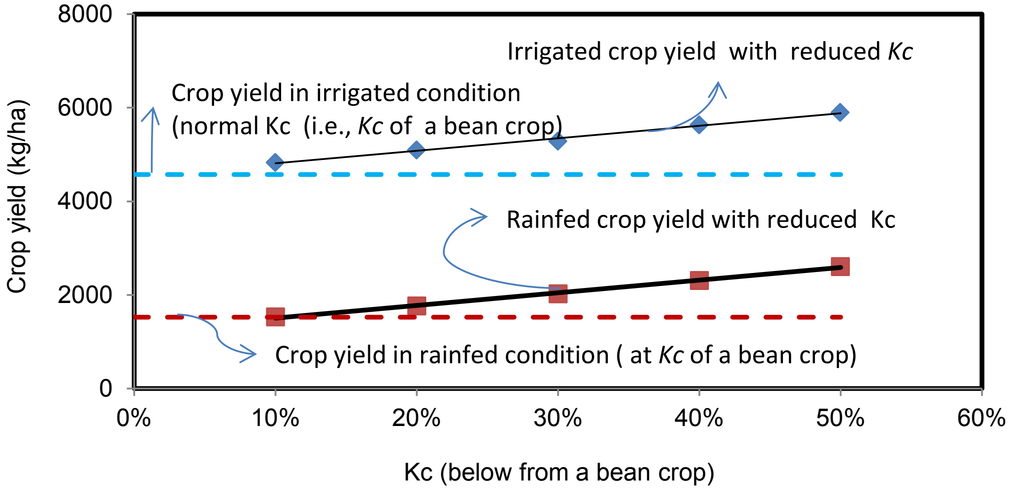
Figure 4c Rainfed crop yield as a fraction of irrigated crop yield (i.e., with OFR system). Dotted line indicates rainfed crop yield as a fraction of irrigated crop yield during average (i.e., normal) precipitation. Light blue with diamond marker line indicates rainfed crop yield as a fraction of irrigated crop yield when precipitation was increased, while red line with rectangle markers indicate rainfed crop yield as a fraction of irrigated crop yield when precipitation was decreased.

3.2 Impacts of crop characteristics on crop yield

To understand how changes in crop characteristics (i.e., *Kc*) potentially will impacts crop yield under rainfed and OFR irrigation system, we performed crop characteristic scenario analyses by changing daily *Kc* values by 10 – 50% (Fig. 5(a), 5(b)). Figure 5(a) shows crop yields when *Kc* was reduced by 10 – 50%. When *Kc* was reduced by 10 – 50%, the crop yield in irrigated condition was increased from 4830 to 5900 kg/ha (shown in blue diamond markers), and in rainfed condition it was increased from 1526 to 2888 kg/ha (shown in red rectangle markers).

Figure 5(b) shows crop yield variations, when *Kc* was increased by 10 – 50%. Under normal *Kc* (i.e., *Kc* of a bean crop), crop yield in irrigated and rainfed conditions were 4574 and 1526, respectively. Crop yield in irrigated condition was reduced from 4277 to 3121 kg/ha, when *Kc* was increased by 10 – 50%, respectively. Crop yield in rainfed condition was decreased from 1316 kg/ha to 685 kg/ha for corresponding changes (i.e., *Kc* was increased by 10 – 50%).

(a)



(b)

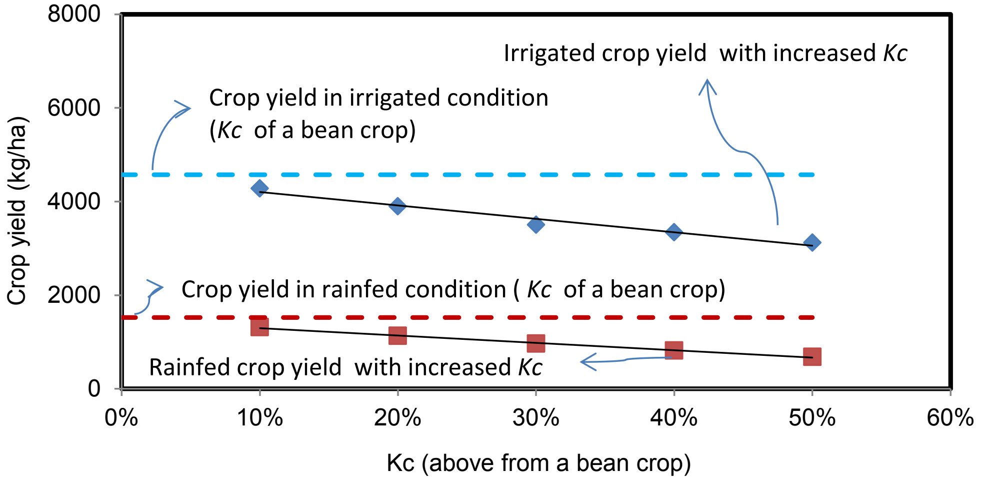


Figure 5a,b Impacts of crop characteristics (i.e., *Kc*) on crop yield: a) *Kc* was reduced by 10 – 50% from average Kc of bean; b) *Kc* was increased by 10 – 50% .

The changes in fractions of rainfed crop yield (i.e., rainfed crop yield/irrigated crop yield) are shown in Figure 5(c). When *Kc* was reduced by 10%, fraction of rainfed crop yield was 0.36, and when *Kc* was decreased by 50%, rainfed crop yield fraction increased to 0.48. Changes in fractions of rainfed crop yield with reduction in *Kc* is shown using red markers in Figure 5(c), while changes in rainfed crop yield fractions with increasing *Kc* is shown using blue diamond markers. Under increased *Kc* values, rainfed crop yield fraction was reduced. For example, when *Kc* was increased by 10%, the fraction was 0.31; however, when *Kc* was increased by 50%, rainfed crop yield fraction was only 0.21.

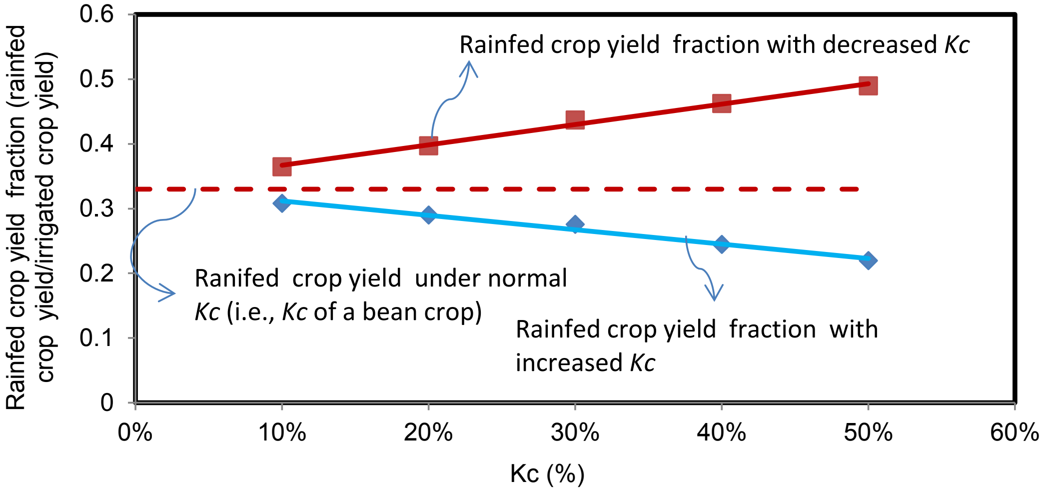


Figure 5c Rainfed crop yield as a fraction of irrigated crop yield (red line with rectangle markers indicates crop yield when Kc was reduced, while blue line with diamond marker indicates crop yield when Kc was increased).

The changes in total water use, overall water use efficiency (*WUE*), *SI, ETc*, and crop yields under various precipitation and *Kc* conditions are listed in Table 1 and Table 2. Table 1 show changes in total water use, *WUE*, *SI, ETc,* and crop yield for irrigated conditions, while Table 2 shows changes in these values under rainfed conditions. In OFR system (Table 1), total water use under normal rainfall condition was 262 mm, which includes *SI*. Water use efficiency was 1.74 kg/m^3, and *ETc* was 318 mm. Estimated crop yield (*Yc*) was 4575 kg/ha. When precipitation was increased by 50%, crop yield increased to 5352 kg/ha, and when precipitation was decreased by 50%, crop yield decreased to 3701 kg/ha. *ETc* at 50% lower precipitation was 76% of the *ETc* at 50% greater precipitation. At 50% lower precipitation the *WUE* was 96% of the *WUE* at 50% greater precipitation.

Table 1 Impacts of rainfall and crop coefficients on crop yields in OFR rainwater harvesting system

Description	total P_{eff} (mm)	*Kc* (range & mean ± stdv	*SI* (mm)	total water use (mm)	*WUE* *(kg/m^3)*	ET_c (mm)	*Yc* *(kg/ha)*	Note
Normal conditions	122	0.15 – 1.25 (0.7±0.4)	108	262	1.74	318	4575	under average pcp
+/- pcp	184 (+50%)	0.15 – 1.25 (0.7±0.4)	112	300	1.78	359	5352	precipitation and crop coefficient were increased and decreased by 50%
	61 (- 50%)	0.15 – 1.25 (0.7±0.4)	110	215	1.72	272	3701	
+/- Kc	122	0.08 – 0.62 (0.3±0.2) (+50%)	120	283	1.10	346	3121	
	122	0.25 – 1.88 (1±0.6) (-50%)	96	193	3.05	244	5900	

Normal conditions represent when precipitation (pcp) was average of three years (1997, 1998, and 1999), and crop coefficient (Kc) was for bean crop (i.e., Kc varied from 0.15 to 1.25). *SI* is supplemental irrigation, *pcp* is cumulative precipitation, *WUE* is overall water use efficiency, *ETc* is estimated evapotranspiration, and *Yc* is calculated crop yield.

When *Kc* was decreased by 50%, crop yield was 89% greater than the crop yield when *Kc* was increased by 50%. The *WUE* at 50% lower *Kc* value was 2.72 times greater than the *Kc* at 50% higher *Kc* value. The *SI* was increased by 1.25 times at 50% greater *Kc* compared to the *SI* at 50% lower *Kc*. Total water use at 50% higher *Kc* value was 1.5 times greater than the total water use at 50% lower *Kc*.

Table 2 shows impacts of rainfall and crop coefficient on total water use and crop yield. Crop yield under normal precipitation was 1526 kg/ha, and total water use was 158 mm without irrigation. At 50% higher precipitation, crop yield was increased by 1.6 times compared to the crop yield of normal precipitation; however, crop yield at 50% lower precipitation was only 35% of the crop yield under normal precipitation condition. Total water use at 50% higher precipitation condition was 1.9 times of the total water use at 50% lower precipitation. The *WUE* at 50% lower precipitation was 43% of the *WUE* at 50% higher precipitation. The crop yield at 50% greater *Kc* value was 24% of the crop yield at 50% lower *Kc* values. The *WUE* values at 50% greater Kc was 21% of the WUE at 50% lower *Kc*.

While comparing crop yields in rainfed and irrigated conditions, the crop yield of irrigated condition at 50% greater precipitation was 2.2 times greater than the crop yield in rainfed condition at 50% greater precipitation. However, when precipitation was reduced by 50%, crop yield of irrigated condition was about 6.8 times greater than the crop yield of rainfed condition. Similarly, when *Kc* was increased by 50%, crop yield at irrigated condition was 4.5 times greater than the crop yield of rainfed condition. The *WUE* of irrigated condition at 50% lower precipitation was 29% of the *WUE* of irrigated condition. At 50% greater *Kc*, the *WUE* value at rainfed condition was 38% of the *WUE* at irrigated condition.

Table 2 Impacts of rainfall and crop coefficients on crop yields in rainfed condition (without OFR system)

Description	total P_{eff} (mm)	*Kc* (range & mean ± stdv	*SI* (mm)	total water use (mm)	*WUE* *(kg/m^3)*	ET_c (mm)	*Yc* *(kg/ha)*	Note
Normal conditions	122	0.15 – 1.25 (0.7±0.4)	No	158	0.96	158	1526	under average pcp
+/- pcp	184 (+50%)	0.15 – 1.25 (0.7±0.4)	No	206	1.17	206	2429	precipitation and crop coefficient were increased and decreased by 50%
	61 (- 50%)	0.15 – 1.25 (0.7±0.4)	No	107	0.51	107	542	
+/- Kc	122	0.08 – 0.62 (0.3±0.2) (+50%)	No	164	0.42	164	685	
	122	0.25 – 1.88 (1±0.6) (-50%)	No	145	1.99	145	2888	

Normal conditions represent when precipitation (pcp) was average of three years (1997, 1998, and 1999), and crop coefficient (Kc) was for bean crop (i.e., Kc varied from 0.15 to 1.25). *SI* is supplemental irrigation, *pcp* is cumulative precipitation, *WUE* is overall water use efficiency, *ETc* is estimated evapotranspiration, and *Yc* is calculated crop yield.

These results indicate that the adaptation of the OFR systems in rainfed areas can be profitable for the rural poor, and assessment of the OFR benefits under various climate and crop conditions will improve water resources management in rainfed regions. Similar findings on the benefits of the rainwater harvesting systems are reported previously. For example, a study by Fox and Rockström (2003) reported a 56% increase in crop yield, when the *SI* was applied to a rainfed crop. Similarly, other studies such as Gunnell and Krishnamurthy (2003), Mialhe et al. (2008), Pandey et al. (2006), and Panigrahi et al. (2001) have also shown that small ponds, which harvest water during rainy seasons, are useful for providing *SI* to crops. A study by van der Zaag and Gupta (2008) reported the increase in the total annual sustainable gross return of rainfed agriculture using the rainwater harvesting system. Other studies have emphasized on combining rainwater harvesting with fertilizer application for improving rainfed crop production. For instance, a study by Rockström and Barron (2007) suggested that the best water productivity in rainfed regions can be achieved when supplemental irrigation is combined with nutrient management and improved tillage practices. Rockström et al. (2002) reported 37 – 38% increase in crop yields when the SI was applied without fertilizers application; however, when the SI was combined with fertilizer application, the crop yield was increased by 70 – 300%. In summary, the study presented here provided insight how the rainfall patterns and crop characteristics potentially can impact the crop yields and water uses of rainfed agriculture with and without rainwater harvesting system. The crop yields of irrigated system were compared with rainfed system. Results suggest that while evaluating the benefits of the OFR system, assessing the impacts of rainfall and crop condition will help optimizing the benefits of the rainwater harvesting system.

4 CONCLUSIONS

This study evaluates the impacts of climate and crop characteristics on crop yield under rainwater harvesting systems, when supplemental irrigation was applied to crops, and crop yield under rainfed condition, when supplemental irrigation was not applied to the crops. Results show that both climate (i.e., precipitation change) and crop characteristics changes the crop production of rainwater harvesting system and rainfed system. Under dry condition, when the precipitation was 50% lower than the normal precipitation, the crop yield under rainwater harvesting system was 6.8 times greater than the crop yield of rainfed system. Under normal precipitation condition, the crop yield of rainfed system was 33% of the crop yield of the irrigated system. The water use efficiency of rainfed system was 55% of the water use efficiency of irrigated system during normal precipitation; however, when precipitation was 50% lower than the normal precipitation, the water use efficiency of rainfed system was 29% of the water use efficiency of irrigated system. The changes in crop coefficient affected water use efficiency and crop yields of rainfed and irrigated conditions. For example, when crop coefficient was increased by 50%, the crop yield of irrigated condition was 4.5 times greater than the crop yield of rainfed condition, and the water use efficiency of rainfed system was 38% of the water use efficiency of the irrigated conditions. The results presented here indicate that while designing the rainwater harvesting system for providing supplemental irrigation for improving crop production, involving the various scenarios of precipitation and crop characteristics are required to calculate the optimum benefits of the rainwater harvesting system.

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