Strategies to improve cereal production in the Terai region (Nepal) during dry season: simulations with aquacrop

Nirman Shrestha*a, Dirk Raesa, Shrawan Kumar Sahb

*Department of Earth and Environmental Sciences, Division Soil and Water Management, Katholieke Universiteit Leuven (Belgium), Celestijnenlaan 200E, BE-3001 Heverlee, Belgium. Email: nirman.shrestha@gmail.com
bDepartment of Agronomy, Rampur Campus, Institute of Agriculture and Animal Sciences, Rampur, Chitwan, Nepal.

Abstract

Strategies to improve cereal yield in Terai (Nepal) were developed with AquaCrop by simulating different scenarios of irrigation and fertilizer management for three dominant soil types with 30 years historical climatic data. Farmers yield increased from 25 to 115% depending on soil type, fertility and irrigation level. Considering the low availability of irrigation water and fertilizers, use of deficit irrigation with 1/4 of the net irrigation requirement (Inet) and fertilizer application below 50% of national recommended fertilizer dose (NRFD) was regarded as the most suitable strategy. For fertilizer applications above 50% of NRFD, deficit irrigation with 1/3 Inet is recommended.

Keywords: winter wheat, spring maize, AquaCrop model, yield stabilization, terai, deficit irrigation, fertilizer management
1. Introduction

Rice (\textit{Oryza sativa} L.), Maize (\textit{Zea mays} L.) and wheat (\textit{Triticum aestivum} L.) are the major cereal crops in Nepal accounting for over 96\% of all food cereal production in Nepal [1]. Ecologically, Nepal is divided into three zones, Terai (Plain), hills and Mountains. The Terai region of Nepal is often called granary of Nepal due to its capability to cultivate and produce food. Although Terai region consists only 23\% of total land area, it produces 56\% of total national cereal production [1]. Rice is typically cultivated during the monsoon season, while maize and wheat are mostly sown during the drier periods before or after the monsoon. Terai region contributes to 65\% and 22\% of the national wheat and maize production of Nepal. The crops are mostly grown under rainfed conditions and with very little use of commercial fertilizers.

Even though wheat and maize are considered as priority crops in the Agricultural Priority Plan of Nepal, the present rates of increase of crop yields are slower than before. Soil erosion, organic matter depletion, acidification, degradation of forest and marginal land, crop intensification and insufficient and unbalanced use of chemical fertilizer have been reported as the main reasons for declining soil fertility [2]. Based on 20 years long field experiments conducted in Terai of Nepal, it has been concluded that nitrogen (N) is the most limiting factor for the production of both rice and wheat [3; 4]. The fertilizer application has been reported low either due to the unavailability or high cost of fertilizers [5; 6]. Most of the farmers used unbalanced fertilizer supply, only applying Urea (i.e. Nitrogen supply only) either due to unavailability of other fertilizers or due to the high costs of fertilizers.

In Nepal, more than 80\% of total precipitation falls during the monsoon, from June to September [7]. With almost 67\% of agriculture based on rainfed cultivation, the annual agricultural output in the dry season is highly dependent on weather conditions. The crop yield varies from year to year depending upon the weather conditions.

The objective of the paper is to assess attainable field management strategies to increase and stabilize cereal yields in the Terai. As there is sufficient water for crops during the monsoon season, this paper focuses on Wheat and Maize cultivated in the winter and spring seasons when only 20\% of average yearly precipitation occurs. A crop water productivity model, which has been calibrated and validated with local field data, was used to assess the effect of different management strategies on the grain production in three major soil types of the region. Given the limited access to irrigation water and commercial fertilizers, this paper focuses on finding ways to increase and stabilize cereal yield with limited water (deficit irrigation) and fertilizer applications.

2. Materials and Methods

2.1 Study Area

The research was conducted in Chitwan district, which can be regarded as a representative location of Terai. Agriculture is predominantly rainfed with 61\% of the area irrigated in the monsoon season and 28\% all year round [8]. During dry season most of farmers depended on groundwater for irrigation. Chitwan is also one of the major producers of maize where it is grown on 75\% of arable land. Wheat is grown in around 19\% of arable area and is third widely grown grain crop in the region. For the period 1998-2002, the average grain yield for winter wheat and spring maize was 1.7 t/ha and 1.6 t/ha respectively. Compared to in farm experiments where wheat yields of 2.7 t/ha [9] and maize yields of 3.5 t/ha [10] were obtained, there is huge margin for improvement of grain crop yields in Chitwan.
The mean monthly reference evapotranspiration (ETo) at Rampur station (84.41°E, 27.61°N, 160 MASL), a representative station for Chitwan, was 120 mm/month [11]. The highest mean monthly ETo value was in May (191 mm) and lowest in December (56 mm) (Figure 1). The minimum temperature was 7 °C in January and the maximum temperature was 36 °C in May. The average yearly precipitation in the area was 2,022 mm, with over 80% in the monsoon season (June to September) (Figure 1).

![Figure 1. Mean monthly rainfall (Grey bars) and mean monthly reference evapotranspiration (Black line with circular markers) at Rampur station in Chitwan.](image)

The soil survey data obtained from National Land Use Project (NLUP) (http://www.nlup.gov.np/) was used for determining the characteristics of the soil in the region. According to NLUP, the three major soil textures of the regions are sandy loam (42%), loam (17%) and clay loam (12%). Additional soil survey was also carried out and soil samples were obtained from 160 random sample points to determine the soil characteristics of the region. The soil texture characteristics of the samples were determined in laboratory using hydrometer [12]. The soil physical characteristics were determined using pedo-transfer function from soil texture [13]. The soil physical characteristics of three major soils are presented in Table 2.

| Soil Type   | Permanent Wilting Point (PWP) vol % | Field Capacity (FC) mm/m | Saturation Point (SAT) mm/m | Total Available Water (TAW) mm/day | Saturated Hydraulic Conductivity (Ksat) mm/day |
|-------------|------------------------------------|--------------------------|-----------------------------|-----------------------------------|---------------------------------------------|
| Sandy Loam  | 9.7                                | 20.1                     | 46.9                        | 104                               | 1277                                       |
| Loam        | 14.1                               | 28.1                     | 45.0                        | 140                               | 313                                        |
| Clay Loam   | 19.7                               | 33.3                     | 43.5                        | 136                               | 132                                        |

2.2 Crop Water Model

A crop water productivity model was used to assess the effect of different management strategies on the cereal production. The FAO AquaCrop model [14; 15; 16] was used for yield simulations. The FAO AquaCrop model has been tested and applied worldwide to derive deficit irrigation schedules, optimize irrigation management, simulate yield response and improve crop production decision support [e.g. 17; 18; 19; 20; 21; 22; 23]. AquaCrop uses a relatively small number of parameters (explicit and mostly intuitive) and pursues an optimum balance between simplicity, accuracy and robustness. AquaCrop is a
multi-crop water productivity model that simulates biomass production based on the amount of water transpired from green canopy cover under the governing environmental conditions. Water, temperature or fertility stress may limit canopy expansion resulting in less crop transpiration. Cumulative biomass production ($B$) is linked to the daily crop transpiration ($Tr$) via the crop water productivity parameter ($WP*$):

$$B = WP* \sum \frac{Tr_i}{ETo_i}$$

Yield ($Y$) is the product of the final biomass multiplied by the harvest index ($HI$). Concepts and equations of AquaCrop are described in detail by Raes et al. (2009) [15] and Steduto et al. (2009) [16]. Before applying the model for simulations it was calibrated and validated with local, experimental data [24]. The calibration and validation statistics results of the wheat and maize are presented in Table 1.

Table 2. Relative root mean squared error (RRMSE), the coefficient of determination ($R^2$) and the Nash–Sutcliffe efficiency (EF) for the calibration and validation of AquaCrop, where n is total number of samples taken during 2010/11 for calibration and during 2010/2011 for validations.

| Crop | Statistics | Above Ground Biomass | Canopy Cover | Soil Water Content |
|------|------------|----------------------|--------------|--------------------|
|      |            | Calibration | Validation | Calibration | Validation | Calibration | Validation |
| Wheat| n          | 16         | 57         | 20         | 73         | 16         | 65         |
|      | RRMSE      | 0.17       | 0.15       | 0.19       | 0.16       | 0.06       | 0.09       |
|      | $R^2$      | 0.94       | 0.95       | 0.91       | 0.89       | 0.88       | 0.72       |
|      | EF         | 0.94       | 0.95       | 0.87       | 0.87       | 0.85       | 0.67       |
| Maize| n          | 12         | 40         | 11         | 42         | 10         | 44         |
|      | RRMSE      | 0.20       | 0.20       | 0.21       | 0.29       | 0.07       | 0.08       |
|      | $R^2$      | 0.97       | 0.96       | 0.94       | 0.87       | 0.74       | 0.79       |
|      | EF         | 0.95       | 0.95       | 0.87       | 0.75       | 0.55       | 0.78       |

The statistical analysis of the comparison between the observed and simulated final grain yields shows very good RRMSE, $R^2$ and EF values of 0.08, 0.90 and 0.87 for wheat and 0.08, 0.97 and 0.96 for maize respectively. In figure 2(a) and 2(b) respectively, the simulated grain yield for wheat and maize is compared with the observed grain yield in a 1:1 graph.

Figure 2. Validation of AquaCrop yield simulation for various soil fertility and water application levels: 1:1 plot comparing simulated with observed grain yield for (a) wheat and (b) maize.
2.3 Management Strategies

The validated AquaCrop model was used to determine management strategies with which the grain production of wheat and maize can be increased in the dry season in Chitwan region. Simulations were conducted with 30 years historical climatic data (1981 – 2011) and for the three different soil types. Five different scenarios of water treatment and six different scenarios of fertilizer treatments were assessed (Table 3). Given the limited water availability outside the monsoon season, only deficit irrigation strategies, suggested by Geerts and Raes, 2009 [25] were considered. It was computed that for wheat the net irrigation requirement (Inet) was 220 mm and for Maize, 310 mm (sandy loam) and 360 mm (loam and clay loam). The deficit irrigation strategies are expressed as a fraction of the water required for Inet (1/4 Inet and 1/3 Inet), and consisted in applying one or two irrigations during the season (Table 3).

Table 3. Water and Fertilizers scenarios used for simulations

| Crop           | Water treatments                                                                 | Fertilizer treatments |
|----------------|----------------------------------------------------------------------------------|-----------------------|
| Winter Wheat   | Rainfed                                                                          | 150% of national recommended fertilizer dose (NRFD) |
|                | Deficit Irrigation (1 application of 55 mm around flowering)                     | 100% of NRFD          |
|                | Deficit Irrigation (1 applications of 35 and 1 of 40 mm, one before and one around flowering) | 50% of NRFD |
|                |                                                                                  | 20% of NRFD           |
|                |                                                                                  | 10% of NRFD           |
|                |                                                                                  | 0% of NRFD            |
| Spring Maize   | Deficit Irrigation (1 application of 25 (sandy loam) or 30 mm (loam and clay loam) after sowing and 1 application of 50 (sandy loam) or 60 mm (loam and clay loam) before flowering) | 150% of national recommended fertilizer dose (NRFD) |
|                | Deficit Irrigation (2 applications of 50 (sandy loam) or 60 mm (loam and clay loam) each, one after sowing and one around flowering) | 100% of NRFD |
|                |                                                                                  | 50% of NRFD           |
|                |                                                                                  | 20% of NRFD           |
|                |                                                                                  | 10% of NRFD           |
|                |                                                                                  | 0% of NRFD            |

To get a good estimate of the initial soil water content (SWC) at sowing or transplanting, the simulations started when the SWC could be well estimated. Table 4 presents the basis for SWC estimation, the initial soil water content, the sowing date and the simulation period.

Table 4. Initial soil water content, sowing data and simulation period used for simulations

| Crop          | Initial Soil Water content                                                                 | Sowing date                                                                 | Simulation Period                                                                 |
|---------------|-------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Winter Wheat  | Average soil water content calculated from 30 year soil water content results at the end of simulation period of monsoon rice | After 15 days of harvesting period for rice and field preparation period, sowing date for the winter wheat was considered as 5 November. | From 5 November to end of cropping period of winter wheat |
| Spring Maize  | Average soil water content calculated after running example simulation of vegetable after monsoon rice. | After 15 days of harvesting period for vegetables and field preparation period, sowing date for the spring maize was considered as 15 February. | From 15 February to end of cropping period of Spring maize |
3. Results and Discussion

3.1 Winter wheat

The simulated yields with rainfed, full irrigation and 2 deficit irrigation strategies for different soil type are presented in Figure 3 (a, b and c). The farmer’s yield of 1.7 t/ha was slightly above the simulated rainfed yield but within the standard deviations. This was most likely due to the fact that the rainfall in 1998-2008 (when observations in farmers fields were made) was 16.9 % above the long-term average for the simulated 30 year period (1981 – 2011). The results showed that the farmer’s yields were constrained by water stress and then by fertility stress when water is available. The standard deviations were always very high in rainfed yields showing highly unstable yields.

Figure 3. Average simulated grain yield (t/ha) of winter wheat for the period 1981-2011 in loam (light grey bars), sandy loam (white bars) and clay loam (dark grey bars) with (a) rainfed (b) one deficit irrigation application (50 or 55 mm) and (c) two deficit irrigation application of 35 or 40 mm each. The horizontal black line indicates the farmer’s yield level [12](CDDC, 2005) and the dashed line indicates the yield level for full irrigation application. Error bars indicate +/- 1 standard deviation.

The results showed that application of deficit irrigation not only increased but also stabilized the yield. The increase in yield level and its stabilization were stronger when more water was applied. A single irrigation application (1/4 of Inet) increased the farmer’s yield by 28 % up to 86 % for different levels of
fertilizer application and soil types. For 2 irrigation applications (1/3 Inet), the yield increase became 39 \% up to 105 \%. The higher TAW of the loamy soils resulted in up to 0.8 t/ha higher yields than in the sandy loams for identical irrigation strategy. It was observed during simulations that the deficit irrigation strategies always had 20 to 50 \% higher water productivity (kg grain yield per m$^3$ water evapotranspired) than full irrigation (data not shown).

Hussein and Al-Jaloud (2005) [26] and Li et al. (2003) [27] has indicated that adequate fertilizer applications promote the crop water use efficiency. Li et al. (2003) [27] has suggested that fertilizer treatments were more effective with irrigation applications. Yield increased up to 1.6 t/ha has been reported due to positive effects of deficit irrigation strategies in different parts of the world [28; 29; 30]. The yield increase up to 1.9 t/ha in our simulations for deficit irrigation applications is synonymous to the earlier reported yield increases.

3.2 Spring Maize

The simulated yield with full irrigation and two deficit irrigation strategies for different soil type is presented in Figure 4(a and b). As maize are sown during the driest period of the year, rainfed maize resulted in crop failures in almost all cases. The simulated yields with a deficit irrigation application of 1/4 Inet were similar to the observed farmer’s yield of 1.6 t/ha. This indicates that most farmer cultivate the spring maize with at least some irrigation. The results showed that the farmer’s yields were constrained by water stress and then fertility stress when water is available.

![Figure 4. Average simulated grain yield (t/ha) of spring maize for the period 1981-2011 in loam (light grey bars), sandy loam (white bars) and clay loam (dark grey bars) with (a) one deficit irrigation application of 25 or 30 mm and one deficit irrigation application of 50 or 60 mm (b) two deficit irrigation application of 50 or 60 mm each. The horizontal black line indicates the farmer’s yield level [12](CDDC, 2005) and the dashed line indicates the yield level for full irrigation application. Error bars indicate +/- 1 standard deviation.](image-url)

The application of deficit irrigation of 1/4 Inet increased the farmer’s yield by 15\% up to 77\% for different levels of fertilizer application and soil types. The yield level and its stabilization increased when more water was applied. The increase of deficit irrigation to 1/3 Inet increased the farmer’s yield by 25\% to 111\%. The differences in maize yield for the various soil types were less pronounced than for wheat, since rainfall was almost negligible in the growing season of spring maize. It was observed during simulations that the deficit irrigation strategies always had 20 to 40 \% higher water productivity than full irrigation (data not shown).
Pandey et al. (2000 a,b) [31];[32] suggested that the simultaneous optimization of both N and water inputs may produce acceptable crop yields and economic return. They also suggested that the fertilizer application at water deficit conditions could be reduced up to half of the fertilizer application at water abundance conditions to maximize the profit. The increasing risk of yield instability with increasing fertility levels in 1/4 Inet deficit irrigation application simulated in the present study corroborated the earlier findings of [31] [32].

4. Conclusion

The yields of grain crops during the dry periods are constrained mainly due to water availability and then due to soil fertility. The increase in fertilizer applications should go parallel with the increase of water applications to keep the yield stabilized over the years. The difference in type of soil (TAW) becomes important when rainfall still plays a vital role in crop production (wheat after monsoon). It can be concluded that for fertilizer applications below 50% NRFD, deficit irrigation application of 1/4 Inet was sufficient. However for the fertilizer application above 50% NRFD, application of irrigations equal to or higher than 1/3 Inet should be considered for stable yields. This study was done without considering crop diseases, weeds and insect infestations in the simulations. Given that the simulation results of farmers strategies are similar to the observed regional average grain yields, it can be concluded that crops are well managed by the farmers, as was observed in the fields during the survey. It should be noted that rainfall of only one station was used. For future studies, the spatial variance of rainfall in the region should also be taken into account.

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