RESEARCH ARTICLE

Yield, water productivity and nutrient balances under different water management technologies of irrigated wheat in Ethiopia

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Abstract

Development of irrigation technologies and agricultural water management systems holds significant potential to improve productivity and reduce vulnerability to climate change. Our study dealt with the behavior of irrigation water productivity, partial nutrient balance and grain yield of wheat under the application of different irrigation water management technologies in the Koga irrigation scheme in Ethiopia. For our analysis, we considered three nutrient fluxes entering and leaving farmers’ fields. Our experimental design had three irrigation blocks with three different irrigation water management practices (wetting front detector, Chameleon soil moisture sensor and farmers’ practice as control) on three farm plots replicated in each block. To calculate irrigation water productivity and grain yield of wheat, the amount of irrigation water applied and the agronomic attributes of wheat yield were recorded during the irrigation period. Further, three input and output variables were considered to determine the partial nutrient balances of nitrogen (N), phosphorus (P) and potassium (K). The results showed that the amount of irrigation water used was 33% and 22% less with a wetting front detector and Chameleon sensors, respectively, compared to the farmers’ practice. The wetting front detector (WFD) and Chameleon sensor (CHS) treatments gave a 20% and 15.8% grain yield increment, respectively, compared to the farmers’ practice plot. The partial nutrient balances of N and K were negative for the wetting front detector and Chameleon sensor practices while it was positive for P in the control (farmers’ practice) treatment. We conclude that irrigation water management with appropriate technologies can improve yield, water productivity and the nutrient utilization. However, further research needs to be conducted on the suitability of irrigation management technologies to achieve full nutrient balance.

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Introduction

Agriculture is the leading sector in the economy of Ethiopia, accounting for about 46% of the gross domestic product (GDP) and almost 90% of export earnings. The agricultural system is based on smallholder production and entirely dependent on rainfed agriculture. So, irrigation has come to play an important role in maintaining food security even though only about 3% of the cultivated land is irrigated due to limited access to water, limited extension and the absence of widespread technology adoption [1, 2].

While the irrigated area is indeed rapidly expanding, water-use efficiency remains as low as 46% within the existing irrigation infrastructure [3]. Substantial water management is therefore needed to ensure efficient utilization of water and other resources [4]. Proper application of irrigation is necessary for high water and crop productivity, better nutrient use by plant roots and protection against environmental degradation [5]. However, in practice, irrigation water is usually applied with limited knowledge, without considering crop water requirements and the soil moisture content.

In the more modern irrigation systems, technologies are being used that enable farmers to grow additional crops [6]. Smallholder farmers in the Ethiopian highlands, however, have not received the benefits of irrigation technologies that could enable them to save water for additional crops, manage plant nutrients and reduce percolation. On the one hand, irrigation in Ethiopia is poorly developed in relation to the potential available; on the other hand, as most of the water is used up to irrigate a limited amount of land, there is little left to serve potentially irrigable land [7].

As irrigation expands in Ethiopia, there is pressure to come up with new strategies to increase its efficiency. Water management for instance could be improved by implementing various practices to increase soil moisture retention capacity and water-use efficiency [8, 9]. Without decreasing productivity, on-farm water use can be substantially reduced through improved irrigation technologies and more efficient water management systems [10]. In addition, such technologies can be important tools to manage the depletion of nutrients in farmers’ fields through runoff and percolation. Plant nutrient loss due to practices that do not consider the status of moisture availability, overutilization of essential nutrients, or underutilization of irrigation water result in constraints like ineffective water use, yield reduction, waterlogging, salinization, leaching of agrochemicals following contamination of groundwater and soil degradation in general.

The objective of this research is to study the impact on water productivity, grain yield and partial nutrient balance of wheat under application of various novel water management technologies in Ethiopia’s Koga irrigation scheme. The technologies we considered in this study were the use of wetting front detectors and Chameleon sensors, which are produced by the Virtual Irrigation Academy in Australia. These technologies were studied in comparison with farmers’ practices as control.

Materials and methods

Description of the study area

Our study area is located in Mecha woreda (district), where the Koga irrigation scheme is situated, at 11°20’57’’ N and 37°02’29’’ E at an altitude of 1,950 m above mean sea level in the Amhara region of Ethiopia (Fig 1). We conducted the study under irrigation conditions from the beginning of October 2018 to the end of April 2019. The Koga irrigation scheme has a total of 11 night storage reservoirs (NSRs) in which water is stored for a 12-hour duration at night when smallholder farmers irrigate their fields. The main canal runs a length of 19.7 km from...
the outlet of the dam. Along the way, it crosses incised drainage channels and tributaries of the Koga and Abay rivers. There are 12 secondary canals with a total length of 52 km that deliver water within their individual command area.

Experimental layout

For this experiment, we selected three irrigation blocks (Chihona, Adibera and Teleta) from the 12 available blocks (Table 1 and Fig 2), using a systematic sampling technique that ensured inclusion of different reaches in the study, one block from the head represented by Chihona, the middle represented by Adibera, and the tail represented by the Teleta reach. Twenty-seven farmers representing the three irrigation water management treatments in each of the three

Table 1. Distribution of irrigation technology treatments among selected farmers within each irrigation block.

<table>
<thead>
<tr>
<th>Irrigation name</th>
<th>Position of block</th>
<th>Land size (ha) for each treatment</th>
<th>No. of participating farmers</th>
<th>Previous crop</th>
<th>Crop for trial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WFD1</td>
<td>CHS2</td>
<td>FP3</td>
<td>WFD</td>
<td>CHS</td>
</tr>
<tr>
<td>Chihona</td>
<td>Head</td>
<td>0.75</td>
<td>1.25</td>
<td>0.75</td>
<td>3</td>
</tr>
<tr>
<td>Adibera</td>
<td>Mid</td>
<td>1.5</td>
<td>1.38</td>
<td>1.25</td>
<td>3</td>
</tr>
<tr>
<td>Teleta</td>
<td>Tail</td>
<td>1.13</td>
<td>1.25</td>
<td>0.75</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3.38</td>
<td>3.88</td>
<td>2.75</td>
<td>9</td>
</tr>
</tbody>
</table>

Notes:
1WFD = Wetting front detector
2CHS = Chameleon sensor
3 FP = Farmers’ practice.
irrigation blocks were selected based on interactions with the community during the farmers’ assembly. These user farmers were identified for intensive monitoring of the on-farm experiment. The area of the farm plots varied from 0.13 ha to 0.63 ha across each block due to different landholding sizes. The Kekeba variety of wheat (Triticum aestivum L.) was used for this study. Fertilizer application ranged from about 60 kg ha\(^{-1}\) to 260 kg ha\(^{-1}\) of diammonium phosphate (DAP) and 80 kg ha\(^{-1}\) to 210 kg ha\(^{-1}\) of urea. Split application of nitrogen was followed, using half at sowing and half at tillering. Each participating farmer was allocated to one of the three irrigation treatments being studied: wetting front detectors (WFD), Chameleon soil moisture sensors (CHS) or control (farmers’ practice, FP). Thus, three farmers participated in each of the three treatments in each block, resulting in three replications per treatment. Our objective was to examine two questions in our analysis: how did nutrient balances, wheat yield and water productivity behave in relation to the three irrigation treatments, and how did the irrigation block position—head, middle or tail-end—influence the above parameters.

The wetting front detectors and Chameleon sensors were installed as appropriate to the root depth of wheat. To guide the participating farmers, Full Stop WFDs were placed at depths of 20 cm and 40 cm as the first treatment to selected group of farmers in each block while the Chameleon soil moisture sensors were installed at depths of 20 cm, 40 cm and 60 cm as second treatment in all blocks. Both wetting front detectors and Chameleon soil moisture sensors were placed at a point three-fourths of the furrow length.

A PR2 Profile (Delta-T Devices Ltd) soil moisture probe was installed at 1 m depth to detect moisture at depths of 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.6 m and 1.0 m in the experimental plots. The moisture profiler was duly calibrated. The PR2 Profile soil moisture reading was used to determine soil moisture at various depths, and the WFDs and Chameleon sensors were used to determine the irrigation schedule so that farmers would know when to stop irrigation. The WFDs were also used to take leaching water samples in all experimental fields for partial nutrient balance analysis.

![A schematic view of the irrigation blocks and the irrigation technology treatments in each block.](https://doi.org/10.1371/journal.pwat.0000060.g002)
Data collection

Quantitative data were systematically gathered from the experimental plots. This included climatic data (such as maximum and minimum temperature, sunshine hours, relative humidity and rainfall) collected from the meteorological station, the amount of water applied to the plots through quaternary canals, harvested grain yield, above-ground biomass and plant height.

The amount of irrigation water applied was measured using V-notch weirs, which were designed and manufactured from a 3 mm thick sheet of metal with standard dimensions. The V-shaped notch in the vertical thin plate was installed perpendicular to the sides and bottom of a straight canal. The line which bisects the angle of the V-notch was set vertically at the same distance from both sides of the channel [11]. The V-notch weirs were installed with a notch height (h) ranging from 2 cm to 5 cm in order to avoid side flows due to the back water flow effects of the weir blockage. These notches were installed on 9 selected quaternary canals just near the respective channel outlets. As per [12], the following equation was applied to measure the flow rate:

\[
Q = 1.38 \tan \left( \frac{\theta}{2} \right) \times H^{5/2}
\]

where \( Q \) = outlet discharge (m\(^3\)/s), \( H \) = effective water (m), \( \theta \) = angle of the V-notch

A total of 27 irrigation water samples were taken from the inlet of the irrigated plots on the date of sowing and during the mid-growth stage of wheat. Using a wetting front detector, leaching water samples were taken based on the growth stage of wheat. The act of sucking up the leaching water below the root zone began when the participating farmers ended irrigation and the deep detector WFD indicator started popping up. A total of 108 such samples were collected during the irrigation season. Rainwater data were collected from the meteorological station whenever it rained in the experiment area during the irrigation period. All the water samples—irrigation water, leaching water and rainwater—were transported to the laboratory within 24 hours. They were analyzed for total nitrogen, phosphorus and available potassium concentration at the Amhara Design and Supervision Works Enterprise (ADSWE) laboratory using an Aqualab photometer integrated with a Palintest analysis system.

Sampling for above-ground biomass and wheat grain yield was randomly carried out. We used a 0.5 x 0.5 m quadrant to mark three sampling points in each farm plot, thereby collecting a total of 27 composite samples. Grain yield was determined by converting the bag measure smallholder farmers use into kilograms per hectare. The weight of the biomass was measured using a sensitive balance in each quadrant and converting into the standard unit. Analysis of the concentration of nitrogen, phosphorus, and potassium was conducted at ADSWE and the laboratory of the Bahir Dar Institute of Technology (BIT) following standard lab procedures.

Irrigation water productivity

The depth of water application by each farmer was calculated as the volume of irrigation water applied using a V-notch weir divided by the area of the experimental plot. Mathematically, this can be stated as:

\[
h = \frac{V}{A}
\]

where \( h \) = depth of water application (m)
\( v \) = volume of water applied (m\(^3\))
\( A \) = area of test plot (ha)
Irrigation water productivity is the total yield produced divided by the amount of irrigation water applied during the irrigation period. While several factors—such as crop management, soil preparation, soil type, variety of crop and climate—influence water productivity [13], for the purposes of this research, they were taken as constant for all the treatments in our study.

\[
\text{Irrigation water productivity (kg m}^{-3}\rangle = \frac{\text{Total yield (kg)}}{\text{Amount of irrigation (m}^{-3}\rangle} \quad (3)
\]

**Partial nutrient balance**

The nutrient balances of nitrogen (N), phosphorus (P) and potassium (K) were calculated as the difference between the sum of inputs and outputs, as shown in Eq 4.

\[
\Delta Nst = \sum N \text{in} - \sum N \text{out} \quad (4)
\]

where, \(\sum N \text{in}\) represents the input (kg ha\(^{-1}\)) of N, P and K

\(\sum N \text{out}\) is the output (kg ha\(^{-1}\)) of N, P and K

\(\Delta Nst\) is the change in N, P and K storage (kg ha\(^{-1}\))

The inputs comprised inorganic fertilizer, nutrients from irrigation water and wet deposition from rainfall. The output was made up of nutrients from the harvested yield, biomass and leaching.

The participating farmers applied only two types of fertilizer during our experiment: urea (46% N) at the rate of 161 kg ha\(^{-1}\) and DAP (18% N, 46% P\(_2\)O\(_5\)) at 100 kg ha\(^{-1}\). One-third of the nitrogen dosage was applied at the sowing stage and two-thirds at the tillering stage. Nutrient availability in the applied fertilizer was calculated as the product of the nutrient in the sample and the total amount of applied fertilizer.

The concentrations of N, P and K in the irrigation water samples were determined and found to be 0.38 mg L\(^{-1}\), 3.6 mg L\(^{-1}\) and 2.65 mg L\(^{-1}\) respectively. These values were used to calculate the nutrient loading from the irrigation water.

Available nutrients in the water samples were expressed as kg ha\(^{-1}\) whereas the total amount of water applied was expressed in terms of m\(^3\). N, P and K added to the soil in the form of wet deposition were estimated as the product of nutrient concentration in the precipitation sample and the total amount of rainfall during the growth period of wheat under irrigation conditions.

The leachate volume of water was determined based on the dimensions of the WFD funnel buried in the soil. The volume of water leached on the plot was calculated as the product of leaching depth and the surface area of the plot. The leaching depth was obtained from the volume of water collected and the surface area of the funnel. The amount of leached nutrients per area was calculated from data on nutrient concentration in soil water and the amount of water applied.

The other outputs considered were biomass and grain yield. The amounts of N, P and K concentration in grain yield and biomass were calculated by multiplying the total grain yield and biomass obtained from the experimental plots.

**Data analysis**

We used the software GenStat (version 18.0) to carry out statistical tests for this study. Prior to data analysis, we performed a normal Q-Q test using this software. Two-way ANOVA analysis was used to assess the interaction effects of the technology treatments and irrigation blocks at the \(P<0.05\) level of significance. Mean comparisons using the LSD (5%) test were done to
observe the differences among treatments to identify the effect of irrigation water management technologies on crop and water production and productivity.

**Ethical considerations**

We obtained ethical approval for this study from the Bahir Dar Institute of Technology of the Bahir Dar University. The lead author also obtained administrative clearance from his employer, the Amhara Agricultural Research Institute. Written informed consent was obtained from all the institutions that participated in this study. Participating farmers were informed that involvement in the study was completely voluntary and that they could withdraw from it at any time without any consequences. By using unique codes instead of names, all our data collection tools were designed to ensure confidentiality. All the information gathered was treated with confidentiality by the research team and would only be used for reporting or publication purposes.

**Results and discussion**

We examined the effects of the irrigation technology treatments and irrigation blocks—and the interaction between these two criteria—on the volume of irrigation water and yield of wheat. We, however, found the interaction between treatments and blocks was non-significant as can be seen in the supplementary material presented in Table A in S1 Text and Table B in S1 Text. Thus, our analysis of variance focused on the irrigation technology treatments.

**Soil characteristics**

The average pH of the soil in the experimental treatments was 4.6 (Table 2), indicating that these are strongly acidic soils [14] with no major difference among the plots. Across the three irrigation blocks, soil in all the study plots was dominated by clay (Table 2). However, there were slight variations in some soil physical properties at the selected sites. According to the Ethiopian Soil Information System [15], concentration of P in the soil from Koga irrigation scheme was significantly high in the range of 12.4–30.3 ppm, which is above the threshold of 10 ppm (Table 2). However, total nitrogen (TN) content was very low (0.2–0.25%), which is below the threshold of 1.5% recommended for crop growth and development [16, 17].

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>WFD</th>
<th>CHS</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean (SD)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH (1:2.5)</td>
<td>4.6(0.26)</td>
<td>4.6(0.24)</td>
<td>4.6(0.33)</td>
</tr>
<tr>
<td>EC (1:2.5)</td>
<td>0.2(0.12)</td>
<td>0.34(0.15)</td>
<td>0.23(0.13)</td>
</tr>
<tr>
<td>OM (%)</td>
<td>3.0(0.52)</td>
<td>3.18(0.34)</td>
<td>0.23(0.13)</td>
</tr>
<tr>
<td>FC (%)</td>
<td>34.1(2.6)</td>
<td>34.4(2.49)</td>
<td>33.9(2.5)</td>
</tr>
<tr>
<td>PWP (%)</td>
<td>23.2(1.93)</td>
<td>24.4(2.77)</td>
<td>22.6(1.8)</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>18.3(9.98)</td>
<td>15.9(11.1)</td>
<td>15.7(1.4)</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>22.6(6.39)</td>
<td>24.8(4.98)</td>
<td>22.7(5.5)</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>59.1(7.1)</td>
<td>59.4(6.61)</td>
<td>61.5(15)</td>
</tr>
<tr>
<td>Total N (%)</td>
<td>0.2(0.01)</td>
<td>0.25(0.01)</td>
<td>0.2(0.01)</td>
</tr>
<tr>
<td>Available P (ppm)</td>
<td>30.3(11.3)</td>
<td>12.4(1.96)</td>
<td>12.6(2.9)</td>
</tr>
<tr>
<td><strong>Soil texture</strong></td>
<td>Clay</td>
<td>Clay</td>
<td>Clay</td>
</tr>
</tbody>
</table>

Note: EC = electric conductivity; OM = organic matter; FC = field capacity; PWP = permanent wilting point.

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Soil property variation can be expressed in terms of the coefficient of variation with a CV <10% indicating low variability [18]. Accordingly, the coefficient of variation for most of the soil physical characteristics had less variability among the blocks and medium variation within each experimental blocks. Some parameters such as total nitrogen, field capacity and pH did have a CV of less than 10%. All our findings on soil characteristics were similar to those reported by earlier studies [7] except available P, which may have been highly affected by the variation in fertilizer application in different plots.

Amount of irrigation water

Compared to the farmers’ practice (control), the WFD treatment conserved irrigation water by 42%, 30% and 27% in the Chihona, Adibera and Teleta irrigation blocks respectively, while the Chameleon soil moisture sensor saved water by 30%, 18% and 17% (Table 3). The variation in water-saving were significantly different (P<0.05) when compared to the farmers’ practice (Table C in S1 Text).

The highest amount of irrigation water applied (573 mm) was for the farmers’ practice (Table 3). Statistically, there was a significant difference between farmers’ practice and irrigation technology use treatments at the 5% level. Due to proximity, the highest amount of irrigation water was applied at the head of the scheme rather than at the tail-end.

Average application of irrigation water was 573 mm, 382 mm and 446 mm per season, respectively, for the farmers’ practice, WFD and CHS treatments (Table 3). Analysis of variance showed that farmers using irrigation water management technology had the maximum output. Overall, compared to farmers’ practices, the application of WFD and CHS reduced the amount of irrigation water applied by 33% and 22%, respectively (Fig 3).

The water saving from WFD of this study is higher than from [19] who reported a water-saving of 24%. However, the water saving reduction (33%) in our research is less than water savings reported by [20], i.e., 43% saving for the wheat crop in Koga irrigation scheme. The water saved through use of WFDs would be sufficient to irrigate more than 20% of the existing irrigated land. This indicates that irrigation water management technologies would have a significant influence on water use. The depth of irrigation water application seen in this study was lower than the seasonal water demand of 480 mm for wheat reported by [20]. This fact indicates greater adoption of technologies by farmers compared to earlier years. Compared to the semi-arid areas in Afar Region of Ethiopia, 380 mm of irrigation water is less than half of what was used for irrigation at the growth stage and similar in magnitude to water use for deficit irrigation [21]. The lower irrigation water from the two technologies, WFD and Chameleon, indicated that smaller amount of water could be used and practically this can be done by deficit irrigation as reported by [22] to save water and irrigate more land.

Table 3. Amount of irrigation water applied under different irrigation technology treatments.

<table>
<thead>
<tr>
<th>Treatment 1</th>
<th>No. of observations</th>
<th>Irrigation water applied (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>FP(Control)</td>
<td>9</td>
<td>494</td>
</tr>
<tr>
<td>WFD</td>
<td>9</td>
<td>330</td>
</tr>
<tr>
<td>CHS</td>
<td>9</td>
<td>392</td>
</tr>
</tbody>
</table>

Notes:
1FP = Farmers’ practice (control); WFD = Wetting front detector treatment; CHS = Chameleon moisture sensor treatment; SD = standard deviation.
2Mean values with different superscript letters are significantly different at the 5% level.

https://doi.org/10.1371/journal.pwat.000060.t003
Wheat yield

The irrigation water management tools we studied in this experiment had a significant effect on yield and biomass ($P < 0.05$ and $P < 0.01$). The highest yields were achieved by WFD users followed by farmers in the CHS treatment. The analysis of variance presented in Table 4 shows a significant difference between these two technology treatments and the farmers’ practice. But there was no significant difference evident between the two technologies themselves (Table D in S1 Text).

There were yield increments of 20% and 15.8% in the WFD and CHS water management treatments, respectively, compared with the farmers’ practice. These yield increases were higher, especially for the WFD treatment, compared to the 13–17% increase reported by earlier research in the same area [20]. Earlier research studies with the same variety of wheat in semi-arid parts of Ethiopia have reported yields in the range of 2.1–3 t ha$^{-1}$ [23]. The same range of yield values was reported by [24] under deficit irrigation in the Afar Region. Our yield results

Table 4. Average yield estimates of wheat under different irrigation technology use treatments.

<table>
<thead>
<tr>
<th>Irrigation treatment$^1$</th>
<th>Yield (t ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean$^1$</td>
</tr>
<tr>
<td>FP (Control)</td>
<td>2.2$^b$</td>
</tr>
<tr>
<td>WFD</td>
<td>2.8$^a$</td>
</tr>
<tr>
<td>CHS</td>
<td>2.6$^a$</td>
</tr>
</tbody>
</table>

Notes:

$^1$ FP = Farmers’ practice; WFD = wetting front detector; CHS = Chameleon soil moisture sensor; SD = Standard deviation.

$^2$ Mean values with different superscript letters are significantly different at ($P < 0.05$).
were in this same range but less than the yields of up to $3.4 \text{ t ha}^{-1}$ reported in Bangladesh [25] and $7 \text{ t ha}^{-1}$ reported in the Mediterranean region of Syria [26]. These reports indicate that there are opportunities to increase yields in the Koga irrigation scheme by introducing different water and soil management technologies.

**Irrigation water productivity**

The average water productivity of 0.73 kg m$^{-3}$ recorded for the WFD treatment differed significantly ($P < 0.05$) from the 0.39 kg m$^{-3}$ obtained under farmers’ practice and 0.59 kg m$^{-3}$ produced by the CHS treatment. Overall variation within and between plots was driven by both crop management and irrigation water management, resulting in relatively large yield variation within treatments as well as large variation of water applied in the experimental plots (Table 5 and Table E in S1 Text).

The average productivity of irrigation water obtained in our study was higher than that reported in past research [21] in the Afar Region. Water-use efficiency in our study ranged from 0.36 kg m$^{-3}$ to 0.8 kg m$^{-3}$. For the calculation by [24] of irrigation water productivity, they used actual evapotranspiration while our study used the total irrigation amount. In our study water-use efficiency for users of irrigation water management technology would be higher than 1 kg m$^{-3}$ assuming an irrigation efficiency of 50%. Water-use efficiency of wheat in various parts of Africa has been reported to be within the range of 0.6–1.7 kg m$^{-3}$ [27]. Our findings for technology users would likely fall within this range too. Gains in productivity of irrigation water using WFD and Chameleon sensor-guided farmers resulted in productivity values close to global values as compared with the farmers’ practice.

**Partial nutrient balance at water management level**

The partial nutrient balance of nitrogen for the WFD, CHS and FP treatments was -49±30 kg ha$^{-1}$, -48±38 kg ha$^{-1}$ and -43±40 kg ha$^{-1}$ respectively (Table 6). These values were observed to have no significant difference among the treatment groups at $P < 0.05$. The slightly high negative values for WFD and CHS treatments indicated that the wheat crop in these field plots consumed inputs properly, leading to high output loss. Wetting front detector and Chameleon sensor technologies minimize the excess water that can leach and prevent a run on the nutrients, thereby enabling the crop to use the nutrients available from the chemical fertilizer. On the other hand, the negative nitrogen balance indicated a depletion of nutrients in the experimental plots, leading to a decline in soil fertility (Table 6).

Farmers who used wetting front detectors reported the highest loss of nitrogen (69 kg N ha$^{-1}$) from above-ground biomass and the lowest loss (0.4 kg N ha$^{-1}$) due to leaching. Due to high outflows, the partial nutrient balance of nitrogen was negative in all the treatments. The partial

<table>
<thead>
<tr>
<th>Treatment$^1$</th>
<th>Productivity of irrigation water (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>FP (Control)</td>
<td>0.53</td>
</tr>
<tr>
<td>WFD</td>
<td>0.85</td>
</tr>
<tr>
<td>CHS</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Note:

$^1$ FP = Farmers’ practice; WFD = wetting front detector; CHS = Chameleon soil moisture sensor; CV = Coefficient of variation.

$^2$ Mean values with different superscript letters are significantly different at ($P < 0.05$).

https://doi.org/10.1371/journal.pwat.0000060.t005
nutrient balance values obtained in this study were high compared with other findings (-1 kg N ha\(^{-1}\), +6 kg P ha\(^{-1}\) and -2 kg K ha\(^{-1}\)) from previous research \[28\] under rainfed conditions in the Amhara region of Ethiopia. Our estimate of the partial balance of nitrogen was similar in trend to findings by research conducted at the national level with values of -47 kg N ha\(^{-1}\) \[29\].

Generally, use of irrigation scheduling technology by the participating farmers led to a higher negative nitrogen partial balance than farmers’ practice although the mean values were not significantly different among the three treatments (Table 6). For nitrogen, removal of biomass was the strongest negative contributor followed by harvested yield.

For phosphorus, the partial nutrient balances were 38±31 kg ha\(^{-1}\), 22±20 kg ha\(^{-1}\) and 39±36 kg ha\(^{-1}\) for the WFD, CHS and FP treatments respectively. The positive balance under all the treatments was ascribed to the lesser P removal in comparison to its addition through the chemical fertilizer. This indicates that our study area does not have the problem of phosphorus deficiency for production of wheat and other major irrigated crops in the Koga irrigation scheme. The highest positive nutrient balance of phosphorus was observed when participating farmers used local practices to monitor the depth of irrigation followed by farmers guided by WFDs as an irrigation water monitoring method (Table 7). Our results for phosphorus were lower compared to research conducted at the Robit Bata watershed under dry conditions \[30\]. This was on account of the fact that the farmers assigned to the control group in our study irrigated with a high amount of water for an unlimited time at the head, middle and tail sections of the scheme. It is clear that when the amount of irrigation water applied is high, the chances

<table>
<thead>
<tr>
<th>Flow</th>
<th>Measured parameter</th>
<th>WFD</th>
<th>CHS</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Inorganic fertilizer</td>
<td>50±13</td>
<td>53±12</td>
<td>50±9</td>
</tr>
<tr>
<td></td>
<td>Irrigation water applied</td>
<td>11±1.3</td>
<td>13±1.4</td>
<td>17±1.7</td>
</tr>
<tr>
<td></td>
<td>Wet atmospheric deposition</td>
<td>0.4±0.2</td>
<td>0.5±0.2</td>
<td>0.4±0.2</td>
</tr>
<tr>
<td>Output</td>
<td>Harvested product</td>
<td>41±12</td>
<td>41±11</td>
<td>35±12</td>
</tr>
<tr>
<td></td>
<td>Above-ground biomass</td>
<td>69±23</td>
<td>73±21</td>
<td>75±28</td>
</tr>
<tr>
<td></td>
<td>Leaching</td>
<td>0.4±0.2</td>
<td>0.6±0.4</td>
<td>0.4±0.2</td>
</tr>
<tr>
<td></td>
<td>Partial nutrient balance(^{2})</td>
<td>-49±30(^{a})</td>
<td>-48±38(^{a})</td>
<td>-43±40(^{a})</td>
</tr>
</tbody>
</table>

Note:
1 WFD = wetting front detector; CHS = Chameleon soil moisture sensor; FP = Farmers’ practice.
2 Mean values with same superscript letters are not significantly different at (P < 0.05).

Table 7. Average phosphorus nutrient balance (kg ha\(^{-1}\)) under three water management technology treatments\(^{1}\).

<table>
<thead>
<tr>
<th>Flow</th>
<th>Measured parameter</th>
<th>WFD</th>
<th>CHS</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Inorganic fertilizer</td>
<td>67±20</td>
<td>54±16</td>
<td>70±30</td>
</tr>
<tr>
<td></td>
<td>Irrigation water</td>
<td>15±2.0</td>
<td>19±4.8</td>
<td>22±2.0</td>
</tr>
<tr>
<td></td>
<td>Wet atmospheric deposition</td>
<td>0.15±0.1</td>
<td>0.17±0.1</td>
<td>0.4±0.2</td>
</tr>
<tr>
<td>Output</td>
<td>Harvested product</td>
<td>4.7±0.9</td>
<td>3.8±1.0</td>
<td>3.5±1.3</td>
</tr>
<tr>
<td></td>
<td>Above-ground biomass</td>
<td>35±12</td>
<td>42±12</td>
<td>43±15</td>
</tr>
<tr>
<td></td>
<td>Leaching</td>
<td>4.5±0.2</td>
<td>5.2±2.9</td>
<td>5.9±6.0</td>
</tr>
<tr>
<td></td>
<td>Partial nutrient balance(^{2})</td>
<td>38±31(^{a})</td>
<td>22±20(^{b})</td>
<td>39±36(^{a})</td>
</tr>
</tbody>
</table>

Note:
1 WFD = wetting front detector; CHS = Chameleon soil moisture sensor; FP = Farmers’ practice.
2 Mean values with same superscript letters are not significantly different at (P < 0.05).

https://doi.org/10.1371/journal.pwat.0000060.t006

https://doi.org/10.1371/journal.pwat.0000060.t007
of phosphorus leaching below the root zone also increase. Thus, addition of inorganic fertilizer and irrigation water were considered the dominant factors in phosphorus erosion (Table 7).

The maximum amount of nutrient gained from inorganic fertilizer and lost from biomass was 70 kg P ha\(^{-1}\) and 43 kg P ha\(^{-1}\), respectively, for the control group farmers. The water management strategies used by the participating farmers could not be expected to have an impact on phosphorus uptake during the growth period of wheat, and the immobile nature of phosphorus reduced biomass loss and output.

The nutrient balance for potassium was \(-9.5\pm3.7\) kg ha\(^{-1}\) for farmers who used WFDs as an irrigation scheduling method; \(-8.5\pm4.3\) kg ha\(^{-1}\) for irrigators who used the Chameleon soil moisture sensors as an irrigation water management method; and \(-2.6\pm3.2\) kg ha\(^{-1}\) for farmers who local practices. The negative nutrient balance showed that sufficient external input of potassium were not given to offset nutrient removal in the yield. Farmers following local practices did not apply potassium as an inorganic fertilizer like DAP and urea. The highest amount of K was imported from irrigation water next to phosphorus and nitrogen and wet atmospheric deposition in their land. Irrigation water contains essential plant nutrients, particularly K, which improves soil fertility [31].

For potassium, the highest amount of the nutrient imported from irrigation with values of 10 kg ha\(^{-1}\), 12 kg ha\(^{-1}\), and 15 kg ha\(^{-1}\) for the WFD, CHS and FP treatments, respectively. On the other hand, the least amount of potassium was measured in leaching water in all the treatments. Statistically, no significant difference was observed among the technology-guided farmers as well as control group farmers in relation to potassium concentration in leaching water. For potassium, the use of mineral fertilizers was negligible. However, K export in the harvested product was relatively high in the WFD, CHS and control treatments, leading to a negative nutrient balance (Table 8). These results from our study were compared with previous studies, as shown in Table 9. The patterns we obtained were comparable with those studies, and the

Table 8. Average partial nutrient balance of potassium (kg ha\(^{-1}\)) under water management technology treatments\(^1\).

<table>
<thead>
<tr>
<th>Flow</th>
<th>Measured parameter</th>
<th>WFD</th>
<th>CHS</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Irrigation water</td>
<td>10±0.9</td>
<td>12±2</td>
<td>15±1.3</td>
</tr>
<tr>
<td></td>
<td>Wet atmospheric deposition</td>
<td>1.3±0.5</td>
<td>1.5±0.5</td>
<td>1.1±0.4</td>
</tr>
<tr>
<td>Output</td>
<td>Harvested product</td>
<td>16±3.9</td>
<td>17±3.0</td>
<td>13±2.7</td>
</tr>
<tr>
<td></td>
<td>Above-ground biomass</td>
<td>4±1.0</td>
<td>4±2.0</td>
<td>4.5±1.7</td>
</tr>
<tr>
<td></td>
<td>Leaching</td>
<td>0.4±0.2</td>
<td>1.1±0.7</td>
<td>0.8±0.7</td>
</tr>
<tr>
<td>Partial nutrient balance</td>
<td>-9.5±3.7(^b)</td>
<td>-8.5±4.3(^b)</td>
<td>-2.6±3.2(^a)</td>
<td></td>
</tr>
</tbody>
</table>

Note:
\(^1\) WFD = wetting front detector; CHS = Chameleon soil moisture sensor; FP = Farmers’ practice.
\(^2\) Mean values with different superscript letters are significantly different at (P < 0.05).

https://doi.org/10.1371/journal.pwat.0000060.t008

Table 9. Comparison of nutrient balances (kg ha\(^{-1}\)) obtained by this study and those reported by previous research in Ethiopia.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Farming system</th>
<th>N</th>
<th>P</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>Smallholder</td>
<td>-43</td>
<td>+39</td>
<td>-2.6</td>
</tr>
<tr>
<td>WFD</td>
<td>Smallholder</td>
<td>-49</td>
<td>+38</td>
<td>-9.5</td>
</tr>
<tr>
<td>CHS</td>
<td>Smallholder</td>
<td>-48</td>
<td>+22</td>
<td>-8.5</td>
</tr>
<tr>
<td>Haileslassie, Priess [34]</td>
<td>Cereal (western Ethiopia)</td>
<td>-46</td>
<td>+3</td>
<td>-75</td>
</tr>
</tbody>
</table>

https://doi.org/10.1371/journal.pwat.0000060.t009
The difference in magnitude was on account of the full nutrient balance in the other studies and the larger scale of study areas [32]. The positive balance of P could be due to the DAP fertilizer with the soil being naturally enriched with P while the negative balance of N and K could be related to the leaching due to high rainfall, use of crop residues for feed and fuel, and potassium fertilizer not being available, which indicates overexploitation [33].

Conclusions

Our study found that farmers who used wetting front detectors and Chameleon soil moisture sensors were able to reduce the amount of water they consume by 33% and 22%, respectively, compared to the control group (farmers’ practice). For both these sets of farmers who used irrigation scheduling technology (WFD and Chameleon sensors), maximum yields were obtained with optimum depth of irrigation water application while the control group had the lowest yield with the maximum amount of irrigation depth. In general, there were 15.8% and 20% yield increments for farmers who used CHS and WFD water management tools respectively. The effect of water management technologies was not only evident in production increments but also in the reduction of loss of water.

However, uptake of phosphorus during the growth phase of wheat was not feasibly affected by the water management practices and the immobile nature of phosphorus decreased the loss of biomass and yield. Therefore, phosphorus is not a critical issue due to its high-dose application and high concentration in the soil. Similarly, potassium is available in the study area as indicated by its negative nutrient balance. But the negative nitrogen balance we found indicates a depletion of nutrients in the experimental plots, sugging a decline in soil fertility. These irrigation water management technologies minimize the excess water that can leach or cause a runoff on the nutrients and the crops benefited from the nutrients provided by artificial fertilizers. In general, nutrient pathways can be critical to understanding the observed nutrient losses; partial nutrient balance calculations do not indicate the sustainability of nutrients in the soil in the context of application of different water management technologies.

Creating awareness and training farmers on use of irrigation scheduling technologies is important to save water and irrigate more land within similar irrigation schemes as Koga in the Ethiopian highlands.

Supporting information

S1 Text. Two-way ANOVA analysis.
(DOCX)

S1 Data. Raw data for analysis.
(RAR)

Acknowledgments

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Software: Alebachew Enyew Tiruye.

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Writing – original draft: Alebachew Enyew Tiruye.

Writing – review & editing: Alebachew Enyew Tiruye, Seifu Adimasu Tilahun.

References


