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Impact on yield and water productivity of wheat by access to irrigation scheduling technologies in Koga Irrigation Scheme, Ethiopia

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Elin Svedberg

ABSTRACT

Impact on yield and water productivity of wheat by access to irrigation scheduling technologies in Koga Irrigation Scheme, Ethiopia

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Improving water use efficiency is included in the Sustainable Development Goals of the United Nations. Ethiopia is a developing country struggling with food production as well as water scarcity. This study presents the results of a statistical analysis of changes in water productivity (i.e. yield versus water usage), wheat yield and irrigation amount by implementation of irrigation scheduling in Koga Irrigation Scheme, north-west Ethiopia. Highest water usage (570 mm), lowest water productivity (0.5 kg m^{-3}) and lowest yield (2800 kg ha^{-1}) were obtained for the control group (i.e. traditional irrigation scheduling, based on experience). All groups which implemented some irrigation scheduling displayed higher water productivity than the control group. The highest water productivity and yield was achieved with a soil moisture sensor (Chameleon) technology, with increases of 58 % and 32 % with respect to the control group, respectively. Nitrogen had a positive effect on both yield and water productivity, however, the interaction effects between applied nitrogen and implemented irrigation scheduling were considered insignificant. This study is concluding that implementation of irrigation scheduling should be a successful approach for improving yield as well as water productivity in Koga.

Keywords: Koga, irrigation scheduling, Fullstop Wetting Front Detector, Chameleon, water productivity

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REFERAT

Utvärdering av hur tillgång till teknologier för bevattningsplanering påverkar skörd och vattenproduktivitet för vete i Koga bevattningssystem, Etiopien

Elin Svedberg

En förbättrad effektivitet i vattenanvändningen ingår i Förenta nationernas Globala mål för hållbar utveckling. Etiopien är ett utvecklingsland med utmaningar i såväl matproduktion som vattenbrist. Denna studie presenterar resultaten av en statistisk analys av förändringar i vattenproduktivitet (dvs skörd per vattenmängd), skörd och bevattningmängd genom implementering av verktyg för bevattningsplanering i Koga bevattningsområde, nordvästra Etiopien. Högsta vattenförbrukning (570 mm), lägsta vattenproduktivitet (0,5 kg m^{-3}) och lägsta skörd (2800 kg ha^{-1}) erhölls för kontrollgruppen. Alla grupper som infört någon typ av bevattningsplanering visade högre vattenproduktivitet än kontrollgruppen (dvs traditionell bevattningsplanering baserad på erfarenhet). Den högsta vattenproduktiviteten och skörden uppnåddes med en vattenfuktsmätare (Chameleon), med ökningar på 58 % respektive 32 % jämfört med kontrollgruppen. Kväve hade en positiv effekt på både skörd och vattenproduktivitet, men interaktionseffekterna mellan kväve och de implementerade bevattningsplaneringarna ansågs försumbara. Denna studie drar slutsatsen att införandet av någon typ av bevattningsplanering bör vara ett framgångsrikt tillvägagångssätt för att förbättra skörd samt vattenproduktivitet i Koga.

Nyckelord: Koga, bevattningsplanering, Fullstop Wetting Front Detector, Chameleon, vattenproduktivitet

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PREFACE

This MSc thesis is part of the bigger project "Using Remote Sensing in support of solutions to reduce agricultural water productivity gaps" (Capacity development for increasing water productivity) (GCP/INT/229/NET), a collaboration between the International Water Management Institute (IWMI) and Bahir Dar University (BDU) supported by the Food and Agricultural Organization of the United Nations (FAO). This study is contributing with an evaluation and statistical analysis of the irrigation scheduling techniques implemented, working with a database developed in the above mentioned project. In addition, a site calibration of the PR2 Profile Probe (Delta-T Devices Ltd) was conducted for soil at Koga irrigation scheme, Ethiopia, for which reference data was made available by Feed the Future through the U.S. Agency for International Development, under the terms of Contract No. AID-OAA-A-13-0005. The research was implemented under a collaborative partnership between the International Water Management Institute and Bahir Dar University.

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I would like thank farmers and data collectors in Koga irrigation scheme for their cooperation during my field work. Menwagaw Tadele, Tewodrose Desale, Habtamu Desalegn and Habtamu Muche from Bahir Dar University have all been of great help and assistance in data collection.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Vikten av att använda vatten så effektivt som möjligt ökar i och med klimatförändringar och en ständigt växande befolkning i världen. Vi behöver inte bara vatten att dricka, vatten är också en viktig komponent i vår matproduktion. Detta har uppmärksammats i Förenta nationernas Globala mål för hållbar utveckling, som bland annat jobbar mot en förbättrad effektivitet i vattenanvändningen. Ett exempel är att det vatten som utnyttjas till odling resulterar i hög skörd. Många utvecklingsländer kämpar med utmaningar i såväl matproduktion som vattenbrist, däribland Etiopien som denna studie utförts i. Här är hanteringen av konstbevattning en viktig fråga, då en övervägande del av vattenanvändningen går till just jordbruk.

Etiopien ligger på Afrikas horn och är till ytan mer än dubbelt så stort som Sverige. De har en växande befolkning på just nu 105 miljoner, varav nästan en fjärdedel lever i fattigdom. Jordbruk är den i särklass vanligaste sysselsättningen. Landet har en uppskattad bevattningsbar mark på 2,7 till 11 miljoner hektar, varav endast 5 % är bevattnad i nuläget. Utveckling av bevattningssystem riskerar dock att orsaka vattenbrist i vissa områden och att öka konflikter om vatten. För att optimera vattenanvändningen har flera hjälpmedel och metoder tagits fram. En av dem är bevattningsplanering, som indikerar när och hur mycket vatten grödorna behöver. Överbevattning är både ett slöseri av vatten och riskerar kväva växterna. Dessutom kan det bidra till en förlust av näringsämnen, då de förs bort av det överflödiga vattnet. I denna studie studeras två sensorer för bevattningsplanering i Koga bevattningssystem, som ligger i nordvästra Etiopien. Båda dessa verktyg är relativt billiga och enkla att använda. De indikerar markens vatteninnehåll på olika djup.

Med i studien var dels bönder som hade någon av de två mätverktygen installerade på sitt fält och dels bönder som fått information om rekommenderad bevattning från de som hade dessa. Dessutom medverkade en kontrollgrupp av bönder som skötte sin bevattning på samma sätt som tidigare, alltså utan dessa mätverktyg. Förhoppningen var att både bönderna som hade ett mätverktyg installerat och de som delgavs information skulle använda vattnet effektivare.

En statistisk analys påvisade att den högsta vattenförbrukningen (570 mm) och lägsta skörden (2800 kg ha^{-1}) erhölls för de bönder som bevattnade som tidigare. Bevattningsmängden var i genomsnitt 14-21 % lägre hos bönder med någon ny typ av bevattningsplanering. Den minskade bevattningen resulterade inte i någon minskning i skörd. Däremot ökade skördarna för alla införda typer av bevattningsplanering utom en. Den högsta ökningen i medelskörd låg på 32 %, jämfört med de som bevattnade på samma sätt som tidigare. Dessa resultat påvisar att minskad bevattning gav bättre skördar än tidigare. Denna studie drar slutsatsen att införandet av någon typ av bevattningsplanering bör vara ett framgångsrikt tillvägagångssätt att minska vattenanvändningen samt öka skördarna i Koga. För att bedöma hur framgångsrik en sådan förändring skulle vara på lång sikt krävs en studietid som omfattar mer än en odlingssäsong.

TABLE OF CONTENTS

1. INTRODUCTION

Water is essential for our existence on Earth and is a resource that should not be taken for granted. In light of growing global population and climate change, better practices of water management need to be developed to ensure food production as well as drinking water in the world. The United Nations has emphasized the problem in 2015, and the 2030 Agenda for Sustainable Development Goal 6.4 (SDG 6.4) specifically addresses the need to improve water productivity in food production (FAO, 2016). Improving irrigation practices is a crucial element of increasing the efficiency of water usage in economically developing countries, which often have both a scarcity of water as well as large and growing populations.

Ethiopia is a country with 105 million inhabitants, 24 % of which live below the poverty line (the World Bank Group, 2017). 85 % of the population is working with agriculture (FAO, 2019). The country is located on the horn of Africa and has a size of about 10^6 km^2, more than double the size of Sweden. The climate varies locally between tropical rainy climate, dry climate and warm temperate rainy climate (Government of Ethiopia, 2018).

The documented area of irrigable land in Ethiopia differs among sources, estimates range from 2.7 x 10^6 ha to 11 x 10^6 ha (Awulachew et al., 2007; FAO, 2016; Nakawuka et al., 2018), of which only approximately 5 % is currently irrigated (Awulachewet al., 2007). Hence, there is much potential for further development of irrigation in Ethiopia. In order to allow for more irrigation while simultaneously using existing water resources as effectively as possible, water usage in irrigated areas must be minimized.

There are several existing tools for irrigation scheduling (see examples in Section 2.1), the two chosen in this study are both cost effective and easy to handle and thus suitable for smallholder farmers (Commonwealth Scientific and Industrial Research Organisation, 2017; Stirzaker et al., 2017). The FullStop Wetting Front Detector shows how deep the water moves down into the soil at irrigation events. The Chameleon Soil Water Sensor is a tool that shows different color depending on how difficult it is for plants to take up water from the soil (Commonwealth Scientific and Industrial Research Organisation, 2017). For further description of the tools, see Section 2.1.

A previous study including a subset of 24 smallholder farmers in the Koga irrigation scheme, not overlapping with the involved farmers in this study, has shown that usage of the Wetting Front Detector can decrease the water usage significantly (Schmitter et al., 2017), which indicates that this topic is of high relevance for the future irrigation in this area. Future investigations of the applicability on a large scale irrigation scheme are needed. In another study, performed in irrigation schemes located in Zimbabwe, Mozambique, and Tanzania, both the Wetting Front Detector and the Chameleon Soil Water Sensor were implemented and quickly adopted by the farmers (Stirzaker et al., 2017).

1.1. OBJECTIVE AND RESEARCH QUESTIONS

This study aims to evaluate the effects of two different irrigation scheduling technologies and the sharing of information with neighboring farmers on yield and water productivity of wheat in the Koga Irrigation Scheme. The implemented devices are the FullStop Wetting Front Detector and the Chameleon Soil Water Sensor.

The main question that will be addressed is how smallholder irrigation development in low tech environments can contribute to more effective water management:

1. How does access to irrigation scheduling technologies affect irrigation, yield and water productivity (here defined as yield per irrigation amount)?
2. Is there a difference in effective water use or yields between farmers owning the irrigation scheduling technology and those receiving information from them?
3. Are there significant differences in the impacts of the implemented tools in different locations in the irrigation scheme (grouped head/mid/tail of irrigation scheme)?
4. Does application of nitrogen have interaction effects together with the implemented irrigation scheduling?
5. Can the existing calibration curve for the PR2 Profile Probe (Delta-T Devices Ltd) be considered representative for the sampled soil moisture?

As water allocation is a both technical and social challenge in large irrigation schemes, this study will help evaluating whether these tools could be effective on a large scale.

2. BACKGROUND/THEORY

2.1. IRRIGATION SCHEDULING TOOLS

Irrigation scheduling is used to determine the optimal amount of water to apply and the timing of irrigation. The objective is to minimize crop water stress and maximize yields. A reduction in over irrigation also reduces leaching of nutrients as well as water logging (Broner, 2005). There are several methods for irrigation scheduling. One example is irrigation based on farmers own knowledge and possibilities, with no use of measurement devices or climate data. Another is scheduling based on measurable climate, crop, and soil factors that affect the soil water balance and crop water use, such as rainfall, potential evapotranspiration, groundwater contribution, stored soil water and crop factor (FAO, 1984). It can be argued that this method is expensive and complicated due to the requirement of education and calculations as well as access to climate data. Therefore, simple and fairly cheap scheduling solutions, based on devices that record the soil moisture variation, can be considered a useful complement to the farmers own knowledge. In this study two such devices were used, which both utilize the soil moisture to give guidelines at what time irrigation is needed and how much water should be applied.

2.1.1. Wetting Front Detector

The Fullstop Wetting Front Detector (WFD) is a funnel shaped mechanical tool installed in the field with its open end upwards (Figure 1). They are used in pairs, one installed at the middle of the root zone and one that reaches down to the end. When field capacity (the maximum water content that the soil can hold) is reached, the water is collected through the open end and the water gets concentrated at the bottom of the funnel. The free water flows through a filter and into a reservoir where it presses up a float that activates an indicator above ground. When the soil dries up, the water is withdrawn by capillary action, and the float goes down again (Stirzaker, 2003; Stirzaker et al., 2004).

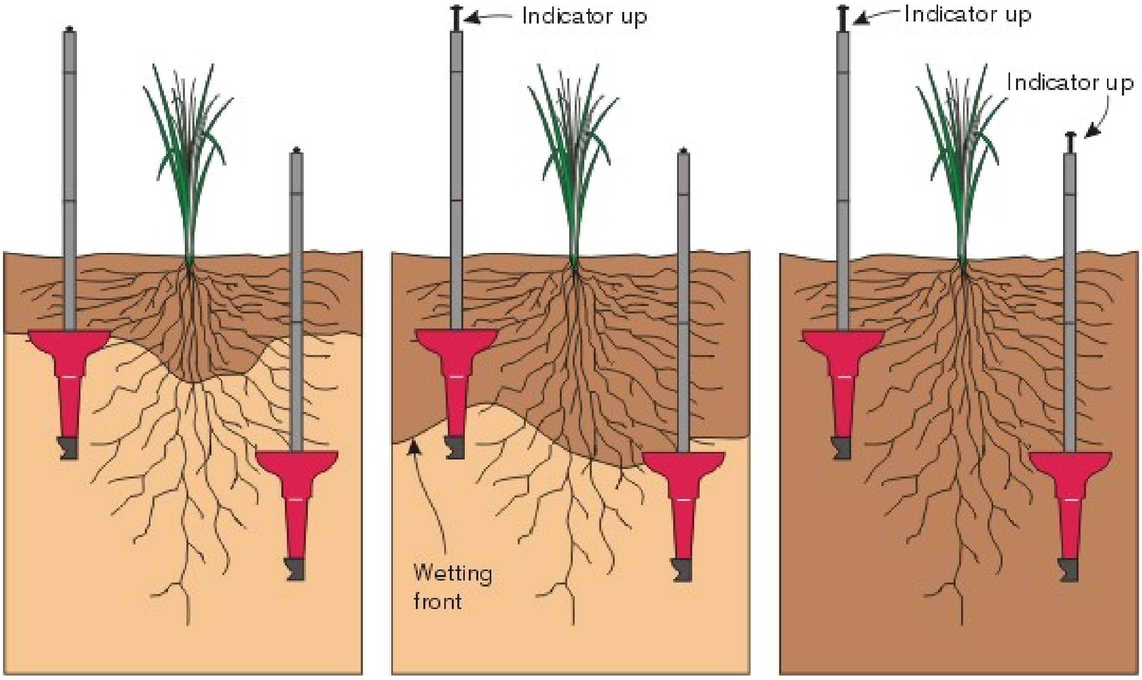

Figure 1: Schematic picture of the WFD and how to use it (figure credit: Commonwealth Scientific and Industrial Research organisation, n.d., reprinted with permission).

2.1.2. Chameleon Soil Moisture Sensor

The Chameleon soil moisture sensor (Chameleon) consists of three resistivity sensors installed at different depths throughout the root zone. The sensors evaluate the tension (how hard it is for the roots to extract water) by measuring the resistance between two electrodes in a specific medium, embedded in a gypsum coating. Attached to the sensors is a reader with a color diode for each depth. The color of the diodes tells whether the soil is wet (0 – 20 kPa), moist (20 – 50 kPa), or dry (> 50 kPa) (Stirzaker, 2014). Tension measurements are not sensitive for different soil types, so Chameleon does not need to be calibrated for this (VIA, n.d.).

3. MATERIAL AND METHODS

The study compiled an existing database containing general field information, total irrigation amount, wheat yield, soil moisture, fertilizer application and top soil properties. A calibration curve for the soil moisture measuring device was established, since they had not been calibrated for the specific soil at location before data was gathered. Finally, this study statistically assessed the impact of the irrigation scheduling devices on yield and water productivity changes, as well as impact and possible interaction effects from nitrogen application. The statistical analyses were performed using the computer programs Excel, R and MATLAB.

3.1. KOGA IRRIGATION DATABASE

The database used in this study (hereafter referred to as Koga Irrigation Database) was developed under the project “Using Remote Sensing in support of solutions to reduce agricultural water productivity gaps” (Capacity development for increasing water productivity) (GCP/INT/229/NET), a collaboration between the International Water Management Institute (IWMI) and Bahir Dar University (BDU) supported by the Food and Agricultural Organization of the United Nation (FAO). The data was collected in Koga Irrigation Scheme during the irrigated cultivation season of December 2017 to June 2018, a short description of the procedures follow below.

A total of 1064 farmers were sampled, of which 421 were in the control group with business as usual. The other farmers were divided into four groups, two equipped with irrigation scheduling technologies, 144 farmers with WFD and 72 farmers Chameleon, and two groups which were receiving information from the farmers with one of the technologies, 278 and 153 farmers respectively. All five groups (control, WFD, Chameleon, WFD info and Chameleon info) were represented in head, mid and tail location of the irrigation scheme; see further description of irrigation scheme in Section 3.2. The farmers with WFD were instructed to aim for the wetting front to lie between the shallow and deep WFD, which was installed at 20 and 40 cm depth, respectively. Farmers with Chameleon were instructed to aim for green colors at all depths, where green color indicates moist soil with soil moisture tension of 20-50 kPa. The sensors of the Chameleon where installed at 20, 40 and 60 cm depth. All farmers were limited by the setup of the irrigation scheme, as they could not irrigate at the same time as their closest neighbors (Tegegne, 2019).

Soil moisture data was sampled with PR2 Profile Probes (Delta-T Devices Ltd) through 144 installed access tubes. The tubes were spatially distributed over the irrigation scheme, covering fields from all groups of irrigation scheduling, including the control. The soil moisture was recorded once per month at the depths of 0.1, 0.2, 0.3, 0.4, 0.6, and 1 m. For irrigation data, the farmers noted the amount of time for each irrigation event. The total water applied was then calculated by using an estimated discharge to field of 0.015 m^3 s^{-1}. Amount and type of fertilizer was noted by farmers and total wheat yield was estimated by count of 100 kg bags produced. Soil texture, content of organic matter, salinity, field capacity and permanent wilting point (water content at tension 1500 kPa, when most plants start to wilt) was determined by lab analysis for top soil in 144 fields.

3.2. LOCATION OF STUDY

Koga Irrigation Scheme is located in the Blue Nile basin, near the town Merawi, which lies in the Amhara region in the north-western part of Ethiopia (Figure 2).

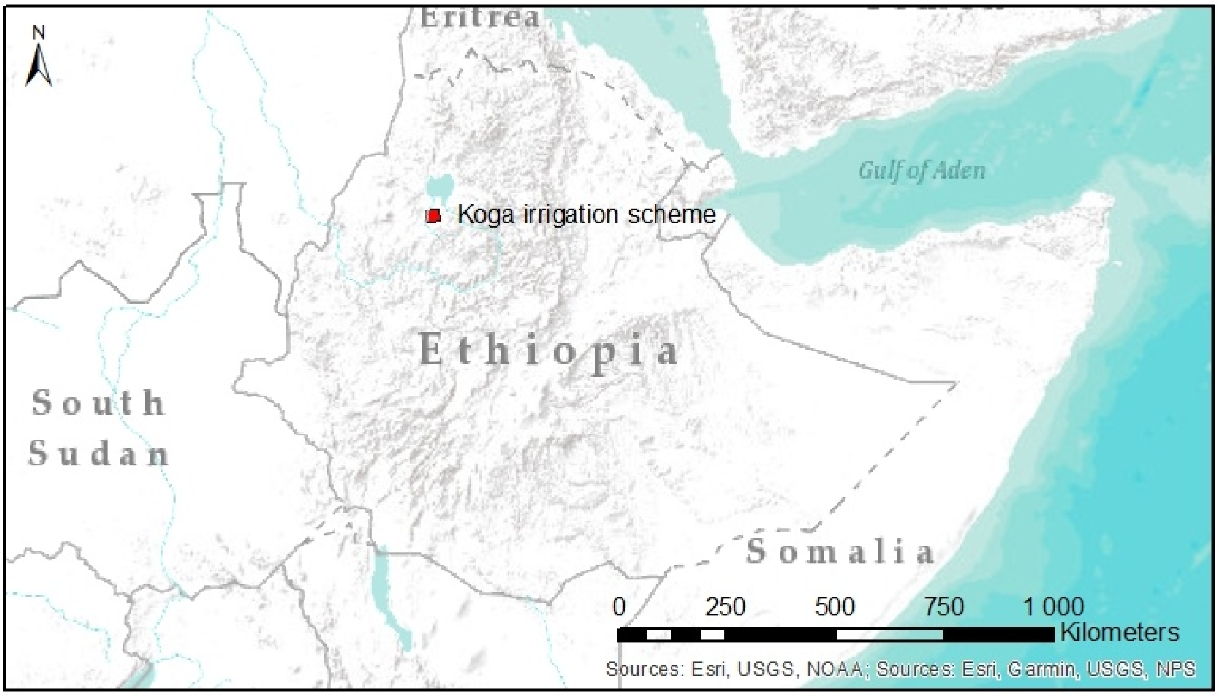

Figure 2: Koga irrigation scheme is marked in red on the map of Ethiopia.

Around 5000 farmers are involved in irrigation practices and the irrigated area is 6000 ha (Agide et al., 2016). The elevation ranges from 2020 m above sea level (masl) in the southern part of the scheme, to 1880 masl in the northern end. The irrigation water is abstracted from a dam (Agide et al., 2016). The main canal, which is paved and has a length of 19.7 km, is passing through the scheme with a flow heading north (Haileslassie, 2016). Secondary canals are connected to the main canal, followed by tertiary and quaternary canals to direct the water to the fields. The irrigation scheme is divided into blocks where head are the fields closest to the inlet of the main channel, mid are the fields further down the main canal, and tail are the fields located in the end of the main canal (Figure 3). Furrow irrigation is used throughout the scheme, where dug furrows allow the water to flood the fields between the rows of crops, using gravity. The water gets infiltrated in the soil and absorbed by the plants.

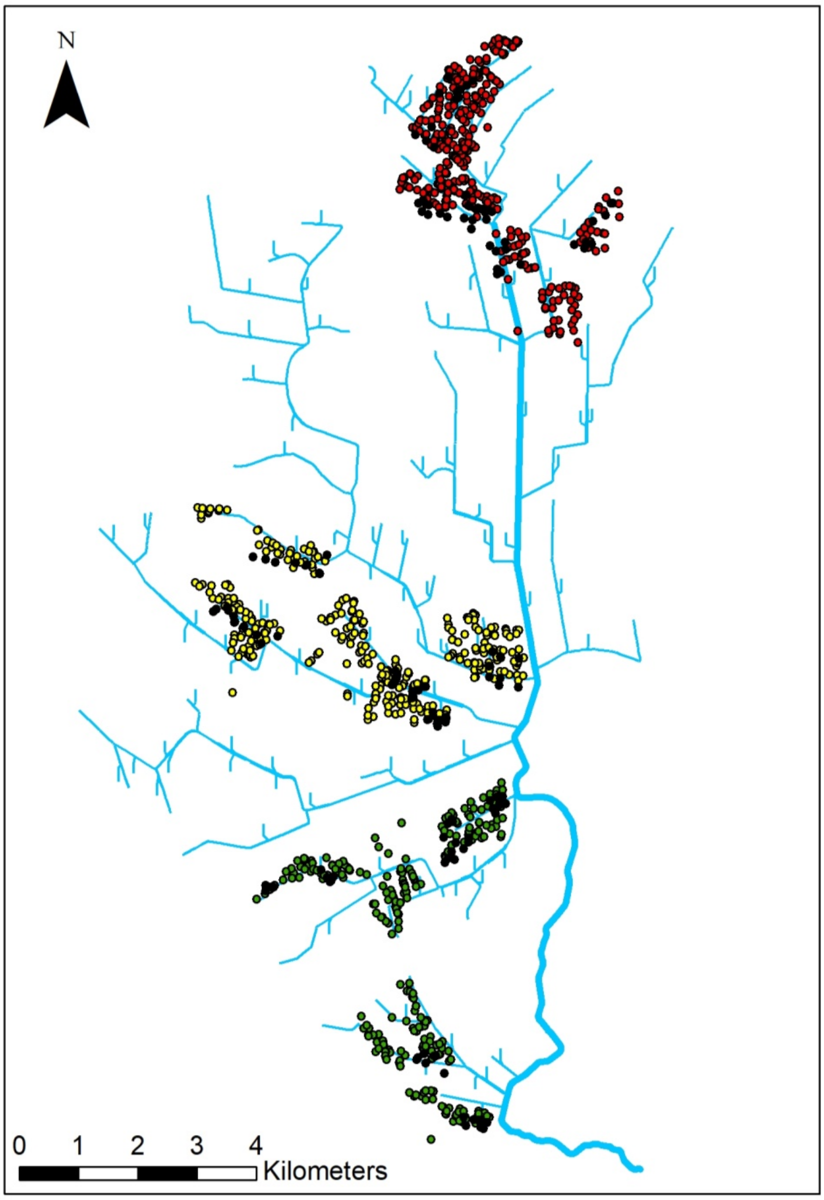

Figure 3: Lines showing the system of canals transporting irrigation water, where the thicker line is the main canal. The fields in this study are grouped by position in the irrigation scheme, where green dots symbolize head group which are situated near the beginning of the mail canal, yellow are mid, and red are tail, near the end. Black dots are showing fields in this study with access tube for soil moisture sampling.

The main crops cultivated during the irrigation season are wheat, maize, potato and onion, with wheat being the by far most common (Agide et al., 2016). Therefore, wheat was chosen as the focus crop in this project. It has a water demand of approximately 480 mm per season (Schmitter et al., 2017). Farmers in Koga use fertilizers, in this study all farmers applied DAP (Diammonuim Phosphate), and many also added Urea. DAP contains 18 % nitrogen and 46 % phosphorous, while Urea contains 46 % nitrogen.

The rainy period usually starts in May and continues into October, with a maximum frequency in July or August. The relative humidity is also highest in July and August, ~75 %, and lowest in March, ~ 43 %. Over the year, the mean monthly relative humidity is 58 %. The mean daytime temperature in the area is 24 °C and the months with the highest average temperature is March to May. The average monthly sunshine hours is 7.2 h d^{-1}, with the highest values in December, 9.9 h d^{-1}, and lowest in August, 4.4 h d^{-1} (Mekonnen and Kebede, 2011).

The topsoil samples of texture from Koga Irrigation Database all fall into the classification of clay by the USDA texture triangle (Figure 4). The range of clay content is 40 – 90 %, while sand and silt content varies from near 0 to 40 %. The bigger the circle in the triangle, the higher is the content of organic matter (OM). The values of OM are ranging 2.0 – 4.5 % with an outlier of 7.7 %, in a total of 144 samples.

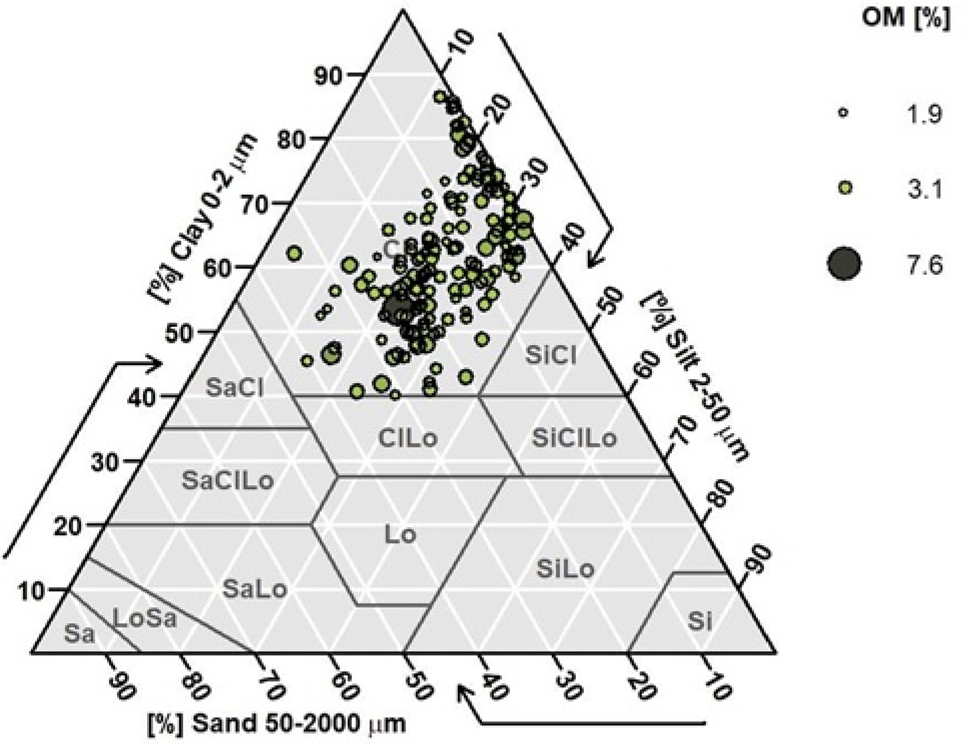

Figure 4: USDA soil texture triangle with bubble plot for organic matter (OM). All points fall within the classification of clay.

3.3. CALIBRATION OF SOIL MOISTURE PROFILER

The PR2 Profile Probe (Delta-T Devices Ltd) had been used to gather soil moisture data for the Koga Irrigation Database during the irrigation season December 2017 – June 2018. The measuring probes use electromagnetic fields to measure the water content in the ground through the soils permittivity. The probes were not calibrated for the specific soils before the data was collected so a consecutive data calibration was required and performed through gravimetric analysis in this study.

3.3.2. Soil Properties

A pedotransfer function was used to estimate field capacity and permanent wilting point based on texture (%), organic matter (%), and salinity (mS m^{-1}) from the Koga Irrigation Database for comparison with the database values from lab analyses. The equations used was soil water characteristics in the SPAW (Soil-Plant-Air-Water) model[1], which are derived from a large USDA soil data base of measured soil water properties by using statistical correlations between soil texture, soil water potential and hydraulic conductivity (Saxon and Rawls, 2006).

For conversion of water content from gravimetric to volumetric, soil bulk density (i.e. mass of dry soil per volume) was sampled. In one field from each position group (head, mid and tail respectively) a pit with the depth of 1 m was dug in the furthermost corner from the inlet of the irrigation system. The sampling depths of 10, 20, 40 and 60 cm were chosen to include top soil and samples above-, in-, and below the hard pan, which was determined at 40 cm with a penetrometer. Shelves were prepared at each depth the day before sampling (Figure 5), and watered through a mesh to simplify sampling. The pit was then covered with a plastic sheet until the following day.

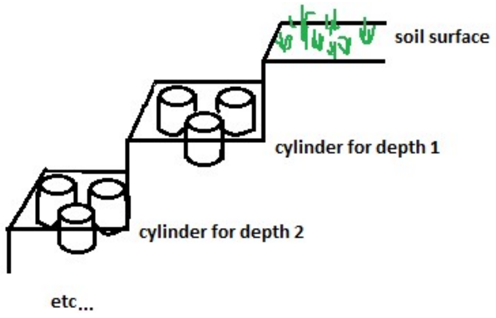

Figure 5: Conceptual picture of the shelves for bulk density samples. The depths were 10, 20, 40 and 60 cm. Four samples were taken from each shelve.

Soil cores were sampled by inserting a cylinder of known volume vertically into the soil until the upper edge was level with soil surface. It was then excavated and both sides of the cylinder cut with a knife. The cores were placed in plastic bags for transportation. For each site, at each depth, four samples were taken. All samples were weighed (accuracy: 0.1 g), put into an oven safe container and dried in 105°C for over 24 h, then weighed again. Bulk density was calculated by Equation 1.

$$\rho_b = \frac{M_s}{V_{tot}} \qquad (1)$$

Where ρ_b = dry bulk density [kg m^{-3}], M_s = weight of the dry soil sample [kg], V_{tot} = total volume of the sample [m^3]

3.3.3. Gravimetric analysis

Five sites with installed access tubes, two located in the head of irrigation scheme, one in mid and two in tail, were used for calibration sampling. For map of locations, see Appendix A. The soil moisture (%) was measured following the manuals recommendation, two consecutive times at the same depths as the bulk density sampling. Soil augers were used to collect four

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[1] Soil-Plant-Air-Water Field & Pond Hydrology, Software Version 6.02.75, K. E. Saxton, USDA Agricultural Research Service in cooperation with the Department of Biological Systems Engineering Washington State University

soil core samples at each chosen depth, circulating around the tube with 90° between each sample (Figure 6).

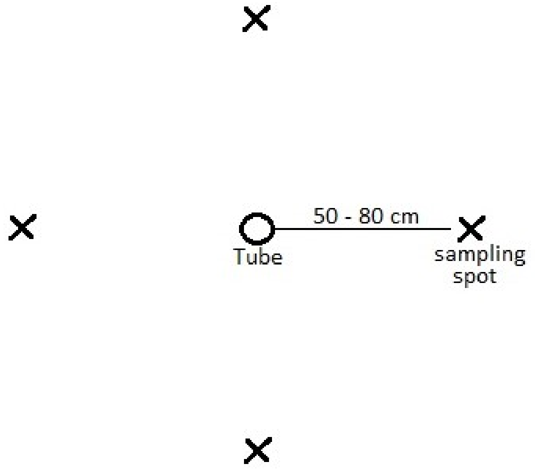

Figure 6: Sketch of soil moisture sampling spots around a soil moisture access tube for PR2 Profile Probe (Delta-T Devices Ltd).

The four soil core samples from the same depth were mixed in a plastic bag and four soil samples were taken of the soil mixture which were put into plastic bags and weighed in field (accuracy 0.01 g). Samples were then dried in 105 °C for at least 24 h, put into a desiccator, and weighed again. Gravimetric soil moisture content was calculated by Equation 2.

$$\theta_g = \frac{M_{water}}{M_s} \qquad (2)$$

Where θ_g = gravimetric soil moisture content, M_{water}= weight of evaporated water [kg], M_s= weight of dry soil [kg]

To calculate the volumetric soil moisture content, the gravimetric soil moisture content was multiplied by the average bulk density for that depth (Equation 3).

$$\theta_v = \theta_g \cdot \rho_b \qquad (3)$$

Where θ_v = volumetric water content [%], θ_g = gravimetric water content [%], ρ_b= dry soil bulk density [kg m^{-3}]

3.3.4. Establishing Calibration Curves

The soil moisture measurements were cleaned using previous data, for further details see Appendix B. Calibration curves were created and compared with a previously made calibration curve for a different profile probe in the same area (Hune, 2016). Additional calibration curves were also created using bulk density values from other research project in the area as a comparison (Jemberu et al., 2017).

3.4. EVALUATION AND STATISTICAL ANALYSIS OF IRRIGATION SCHEDULING TECHNOLOGIES

3.4.1. Data Processing

Only farmers taking part in full season measurements and sampling were included in this study. When important data were missing or inconsistency occurred a farmer was also removed from the data. A total of 941 farmers were therefore included out of originally 1064. The yield, irrigation and fertilizer data sets were verified by comparison with data from previous studies (Schmitter et al., 2017; Haileslassie, 2016; ETH, 2012). In this study, the water productivity was defined as yield per irrigation amount (Equation 4).

$$Water\ productivity\ (kg\ m^{-3}) = \frac{Yield\ (kg)}{Irrigation\ amount\ (m^3)} \tag{4}$$

3.4.2. Statistical Data Analysis

The distribution of data and possible relationships were graphically evaluated. Violin plots with embedded box plots were made for yield, irrigation and water productivity (yield per irrigation), where the data was grouped by either irrigation scheduling (Control, WFD, information from WFD, etc) or placement in the irrigation scheme (head, mid, tail). Empirical cumulative density function plots were also compared between the groups. For continuous variables, scatter plots were evaluated.

Multiple linear regression is a well-known statistical method to model the relationship between a response variable (Y) and several explanatory variables (X_1-X_k). Their relationship is shown in Equation 5.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \epsilon \tag{5}$$

Where β_0 is the intercept, β_1- β_k is the slope coefficient for corresponding explanatory variable and ϵ is the error (noise in the data).

To get an insight in which variables are appropriate to test in the model, scatter plots can be evaluated for continuous variables and box plots for categorical data. When evaluating the model it is important to look at the residual plots. Patterns or curvature indicates that the data needs to be transformed. Care should also be taken for possible leverage or influence of certain points. Outliers in the data can have a large and misleading effect on the model. In simple linear regression these points are easier to detect as the data easily can be plotted. Another problem that might occur in a model is (multi)collinearity. This happens when two or more explanatory variables are closely related to each other. This can for example cause the model to be unstable i.e. change drastically as a few of the data values are changed. A way to avoid this is to exclude variables that are closely related. If two variables explain the same phenomenon, excluding one of them should not affect the models power of explanation.

An optimal model explains as much of the variance in the response variable as possible, with as few explanatory variables as possible. As the R^2-value always increases with the number of explanatory variables, this is not a good indicator. It is preferable to look at the adjusted R^2, which takes the models degrees of freedom and least square error into account (Helsel and Hirsch, 2002).

To determine the most important parameters and interactions for yield and water productivity, multiple linear regression modeling was performed by forward selection, i.e. adding explanatory variables and interactions until higher complexity no longer results in a significant improvement of fit. The explanatory variables tested for both models were irrigation scheduling, position in irrigation scheme and nitrogen application. The models were tested with double and triple interactions together with main effects. Before modeling, the data was checked for normality through visual evaluation of the box and scatter plots. The residual plots from the models were analyzed for homoscedasticity. The models were then evaluated by their adjusted R^2-value, coefficients and an ANOVA test to summarize the influence of each factor. Finally, a least significant differences (LSD) between paired means was used, to determine significant differences between the categories in irrigation scheduling and position.

4. RESULT ANALYSIS

4.1. CALIBRATION OF SOIL MOISTURE PROFILER

4.1.1. Soil Properties

The field capacity (FC) from lab analysis in Koga Irrigation Database, 29.7 – 45.3 %, falls within the range of previous studies in the area by Asres (2016) and Alemie (2009) (Table 1). The whole interval of modeled FC, ranging 37.7 – 46.0 %, is higher. The range of permanent wilting point (PWP) from the Koga Irrigation Database, 15.1 – 30.8 %, is also similar to the total range found by Asres (2016) and Alemie (2009). The modeled PWP ranged slightly higher, 24.1 – 35.2 %.

Table 1: Modeled values of field capacity (FC) and permanent wilting point (PWP) using the SPAW model, together with sampled values from previous studies in the Koga area.

FC [%]	Koga Irrigation Database Lab analysis A1	This study Pedotransfer function A2	Asres, 2016 Lab analysis B	Alemie, 2009 Lab analysis C
median	34.2	42.8	24.1-27.4	33.7-37.4
max	45.3	46.0		
min	29.7	37.7		

PWP [%]	Koga Irrigation Database Lab analysis A1	This study Pedotransfer function A2	Asres, 2016 Lab analysis B	Alemie, 2009 Lab analysis C
median	22.8	30.7	18.5-22.2	25.9-30.3
max	30.8	35.2		
min	15.1	24.1		

The obtained values of bulk density ranged from 1.03 to 1.22 g cm^{-3}, which is lower than previously sampled by Jemberu et al. (2017) and Klik et al. (2018) (Table 2). However, the bulk density samples are not from the exact same location and the highest bulk density (Jemberu et al., 2017) was sampled in slopes of 5 - 30 %, while the samples in this study come from fields that are level.

Table 2: Calculated bulk density (BD) from soil core samples in Koga irrigation scheme, together with other bulk densities from the near area, D (Jemberu et al., 2017) and E (Klik et al., 2018). Note: *Based on one sample only.

BD [g cm^{-3}]		This study Lab analysis KOGA IRRIGATION SCHEME			Jemberu et al, 2017 Lab analysis	Klik et al, 2018 Lab analysis
	Depth	Head	Mid	Tail	D	E
	10	1.22	1.14	1.15		
	20	1.17	1.21*	1.13	1.28-1.44	1.19-1.26
	40	1.13	1.12	1.06		
	60	1.14	1.11	1.03		

4.1.2. Establishing Calibration Curves

The calibration curve for the PR2 Profile Probe with the bulk density sampled in this study (Table 2) has a R^2-value of 0.73 (Figure 7). An older calibration curve made in Koga irrigation scheme for another probe of the same kind has a similar R^2-value of 0.77, with bulk density 1.06 ± 0.09 g cm^{-3} (Hune, 2016). The curves have similar slopes of 1.29 (this study) and 1.15 (Hune, 2016) (Table 3), although there is a difference in position, y-intercept 21 and 29 % respectively, which can be related to the higher bulk density sampled in this study. Both the calibration curve obtained in this study and the one by Hune (2016) crosses the highest values of FC by Alemie (2009).

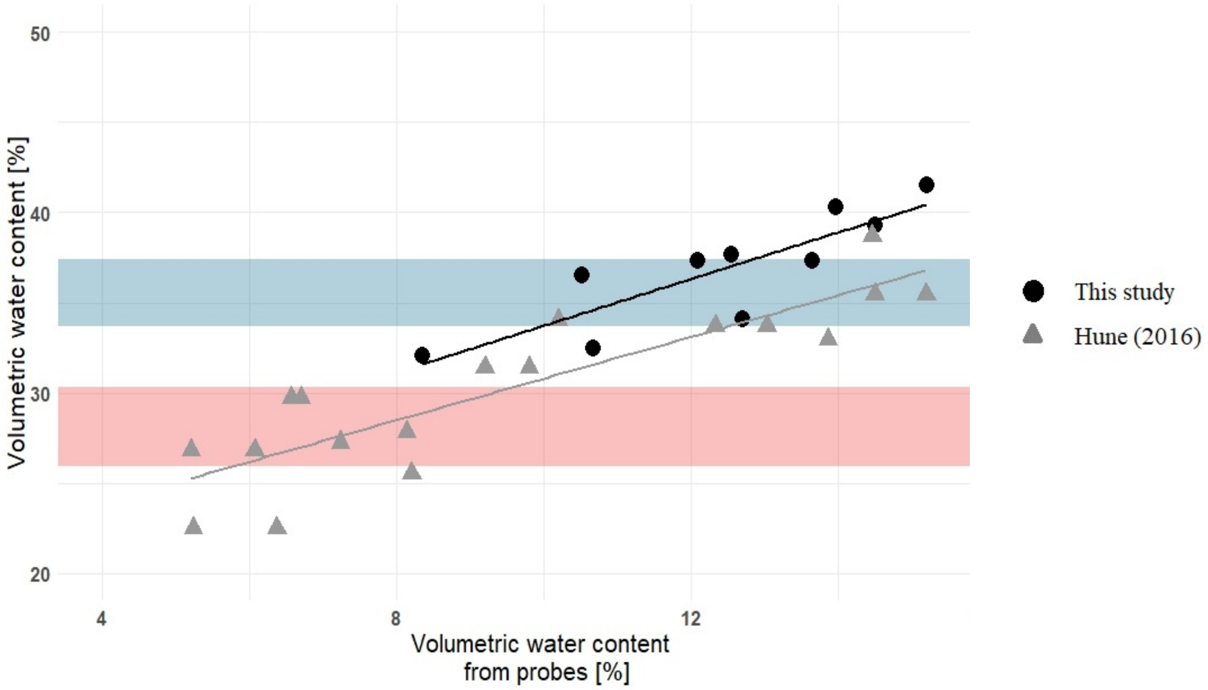

Figure 7: Calibration curve for the PR2-UM-5.0 Profile Probe (black) using bulk density values obtained from soil samples. In the plot is also an old calibration curve (Hune, 2016) for another profile probe in the same area (grey). The shaded areas represent the interval of FC (blue, upper) and PWP (red, lower) concluded in a previous study in Koga (Alemie, 2009).

The calibration curves obtained by inserting lowest respectively highest bulk density determined in another field study in Koga catchment (Jemberu et al., 2017) had a slightly higher R^2-value of 0.80 (Table 3). The only effect of bulk density was a vertical dislocation of the curve. Both curves end up far beyond the FC in the study by Alemie (2009).

Table 3: Equations and R^2-value for calibration curves. When altered, bulk density (BD) is specified

Calibrationcurve	Equation	R²
This study	y = 1.29x + 21	0.73
Hune, 2016	y = 1.15x + 19	0.77
This study, BD = 1.28	y = 1.42x + 24	0.80
This study, BD = 1.44	y = 1.60x + 27	0.80

4.2. EVALUATION AND STATISTICAL ANALYSIS OF IRRIGATION SCHEDULING TECHNOLOGIES

There is an indication of a boundary function in the relationship between irrigation and yield, which is illustrated by a black line with a slope of 18 kg ha^{-1} mm^{-1} and x-intercept of 40 mm. (Figure 8). This boundary line is similar to the one proposed by French and Schultz (1984a and b), which was inserted to the plot for comparison purpose (dashed, red). Their line was determined by wheat yields as a function of evapotranspiration in south eastern Australia and had a slope of 20 kg ha^{-1} mm^{-1}. Here the x-intercept was set to 60 mm, although the study concluded an interval between 30 and 170 mm depending on environmental conditions (French and Schultz, 1984a and b). Another study by Sadras and Angus (2006) compiled yield data from several dry environments, namely China Loess Plateau, south eastern Australia, North American Great Planes and Mediterranean basin, and used a similar boundary function; slope of 22 kg ha^{-1} mm^{-1} (Angus and van Herwaarden, 2001) and x-intercept of 60 mm (Sadras and Roget, 2004). Additional scatter plots of water productivity against yield and irrigation can be found in Appendix C.

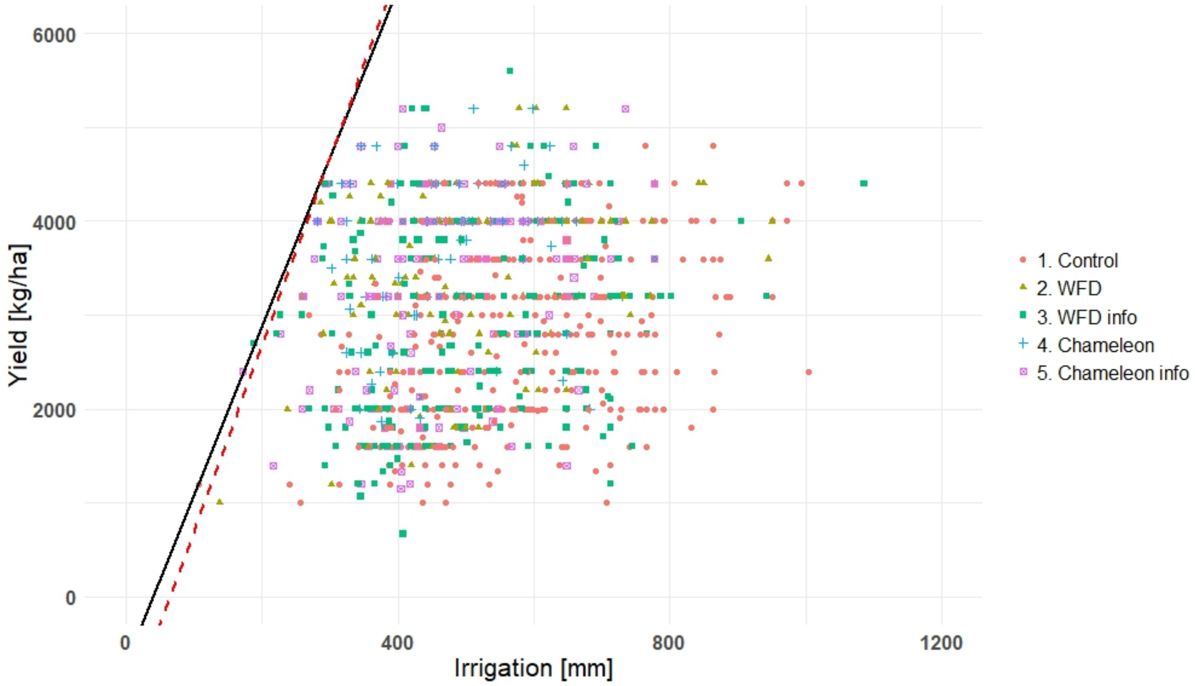

Figure 8: Impact of irrigation on yield. The lines use the frontier concept from French and Schultz (1984), where red has slope: 20 kg ha^{-1} mm^{-1} and x-intercept: 60 mm (French and Schultz, 1984) and black has slope: 18 kg ha^{-1} mm^{-1} and x-intercept: 40 mm. The function was originally made for yield and evapotranspiration.

The distributions and total ranges of yield are similar between the different groups of irrigation scheduling tools, although the median values are higher for WFD, Chameleon and Chameleon info, 3400, 4000, 3600 kg ha^{-1} respectively, compared to the control group and WFD info with medians of 2800 kg ha^{-1} (Figure 9 A). The control group corresponds well with yields previously recorded in the area. In a recent study in Koga and Meki irrigation scheme wheat yield was ranging from 1500 to 4200 kg ha^{-1}. The study included 13 plots, where some were controls (2600 ± 800 kg ha^{-1}) and some had the WFD technology (2600 ±

900 kg ha^{-1}) (Schmitter et al., 2017). In 2011 the wheat yield in the Amhara region was recorded to 1700 kg ha^{-1}, and the overall range in Ethiopia was 700 to 2800 kg ha^{-1} (ETH, 2012). Another study in Koga found wheat yields up to 1600 kg ha^{-1} (Haileslassie, 2016).

For farmers in the control group, WFD info or Chameleon info, the lowest 20 % of yield was ≤ 2000 kg ha^{-1} (Figure 9 B). In the Chameleon group the lowest 20 % ranges between 1800 – 3000 kg ha^{-1}.

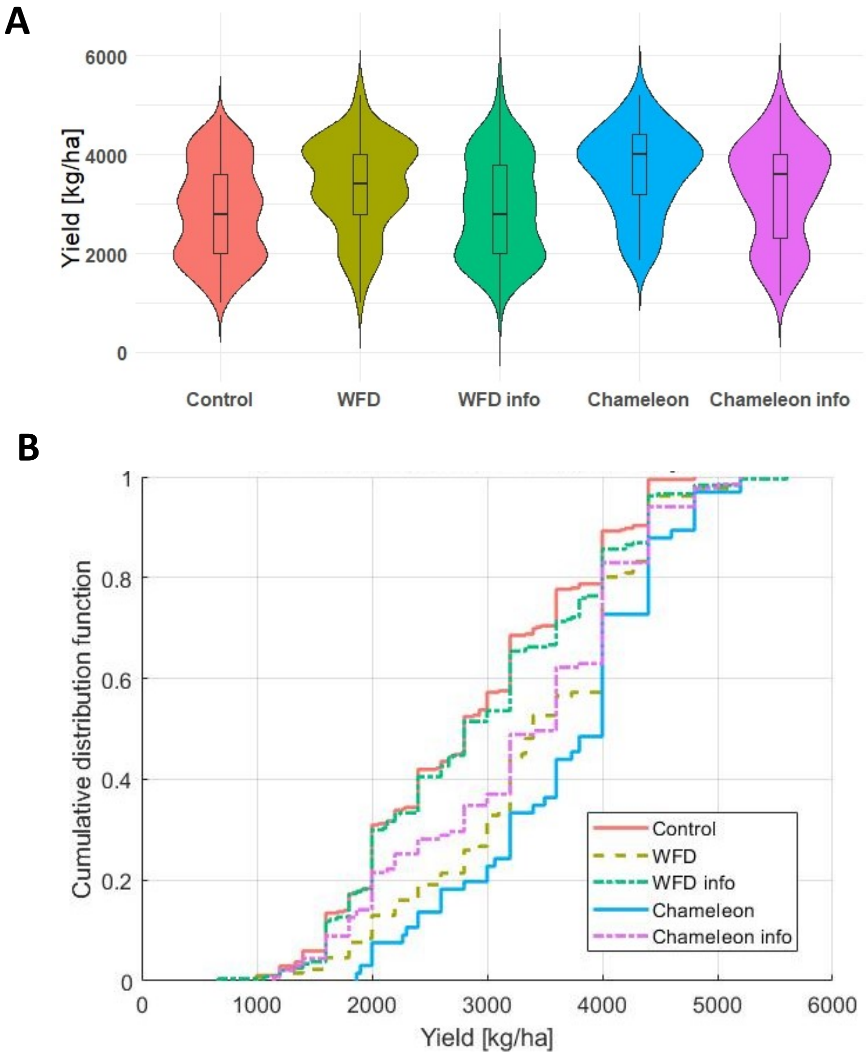

Figure 9: A) Violin plots of yield divided by groups of method with embedded box plots showing median, interquartile range (25th and 75th percentiles) and total range of the data. B) Cumulative distribution plot of yield for the different irrigation scheduling methods.

The median value of total irrigation over the season is similar for all technologies ranging 450 – 490 mm, while the control group had a median of 570 mm (Figure 10 A). Farmers irrigating more than 600 mm are 40 % in the control group, compared to 20 % in Chameleon and Chameleon info (Figure 10 B). Assuming a water demand of 480 mm per season for wheat (Schmitter et al., 2017), the irrigation recorded in Koga Irrigation Database falls within a reasonable range. However, many farmers still irrigate well above the water demand in all groups.

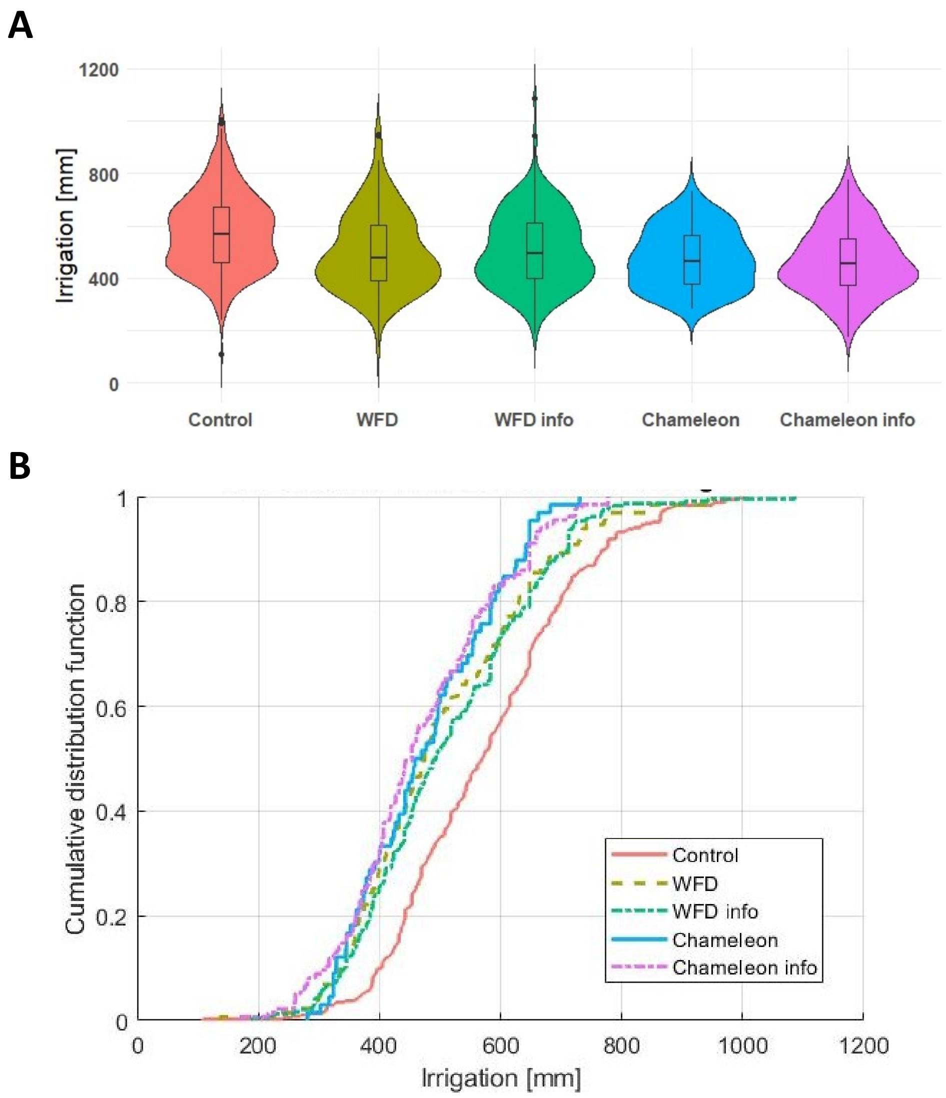

Figure 10: A) Violin plots of total irrigation divided by groups of method with embedded box plots showing median, interquartile range (25th and 75th percentiles) and total range of the data. B) Cumulative distribution plot of total irrigation for the different methods.

The median of water productivity was highest for Chameleon with a difference of 0.1 kg m^{-3} down to the second highest, Chameleon info and WFD with medians of 0.69 and 0.68 kg m^{-3} respectively (Figure 11 A). Lowest median water productivity was achieved by WFD info and control group (0.53 and 0.49 kg m^{-3} respectively). In the control group 50 % of the farmers had water productivities below 0.5 kg m^{-3}, whereas this interval only covered 10 % of Chameleon users (Figure 11 B). Water productivities exceeding 1 kg m^{-3} was reached by 10 – 20 % of the farmers with irrigation scheduling technologies or information, while only 2 % of the control group achieved the same results.

The previously determined water productivity in Koga is ranging from 0.08 to 0.49 kg m^{-3} (Schmitter et al., 2017), the large differences from this study origin in the differences in irrigation. Water productivity for wheat in Pakistan has been recorded up to 1.8 kg m^{-3} (Hassan, Hussain and Akbar, 2005), indicating that the water productivity in Koga could be improved even further. The water use efficiency for wheat in terms of grain yield per transpiration has globally been recorded in magnitudes of 1.0 – 1.7 kg m^{-3} (French and Schultz, 1984) and is now expected to have a maximum of 2.2 kg m^{-3} (Sadras and Angus, 2006). In a review study by Zwart and Bastiaanssen (2004), water use efficiency defined by yield per actual evapotranspiration ranged from 0.6 – 1.7 kg m^{-3}. However, it should be noted that water use efficiency is measured differently and therefore always are higher than values of water productivity based on water input.

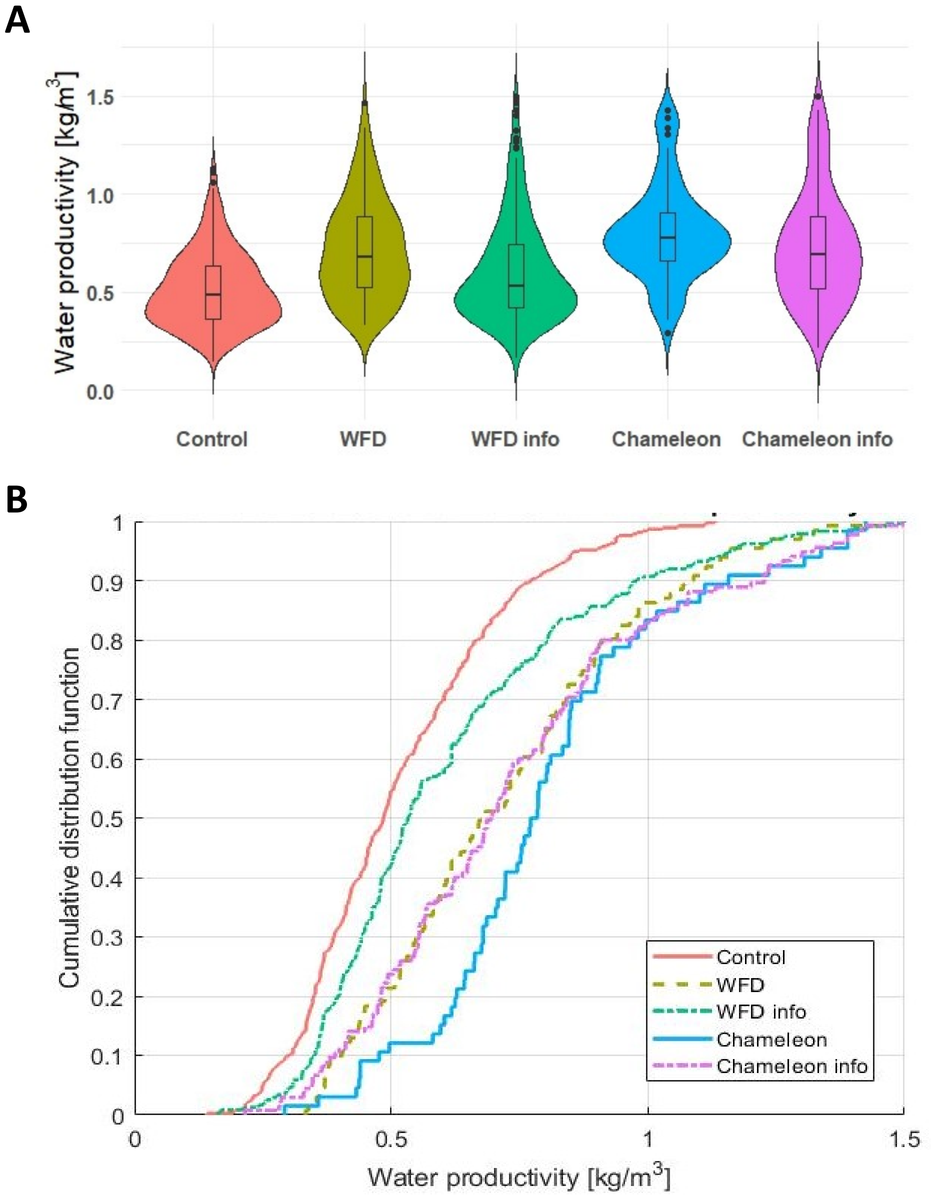

Figure 11: A) Violin plots of water productivity divided by groups of method with embedded box plots showing median, interquartile range (25th and 75th percentiles) and total range of the data. B) Cumulative distribution plot of water productivity for the different methods.

When evaluating the importance of location in the irrigation scheme instead of method used, the mid and tail have a slightly higher median yields (3200 kg ha^{-1}) than head (2800 kg ha^{-1}) (Figure 12).

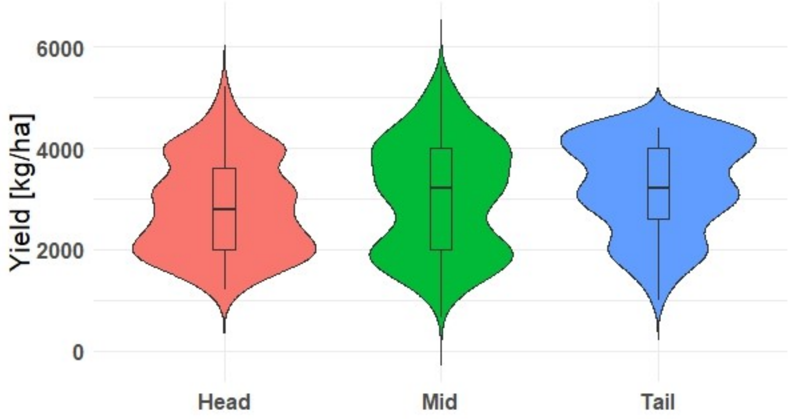

Figure 12: Violin plots of yield divided into groups of position in the irrigation scheme with embedded box plots showing median, interquartile range (25th and 75th percentiles) and total range of the data.

The median of total irrigation are head 540 mm, mid 480 mm and tail 530 mm (Figure 13).

Figure 13: Violin plots of total irrigation divided into groups of position in the irrigation scheme with embedded box plots showing median, interquartile range (25th and 75th percentiles) and total range of the data.

The medians of water productivity are similar for mid and tail, 0.61 and 0.62 kg m^{-3} respectively, while head has a median of 0.53 kg m^{-3} (Figure 14). These results agree well with the median values of yield and irrigation (Figure 12 and 13).

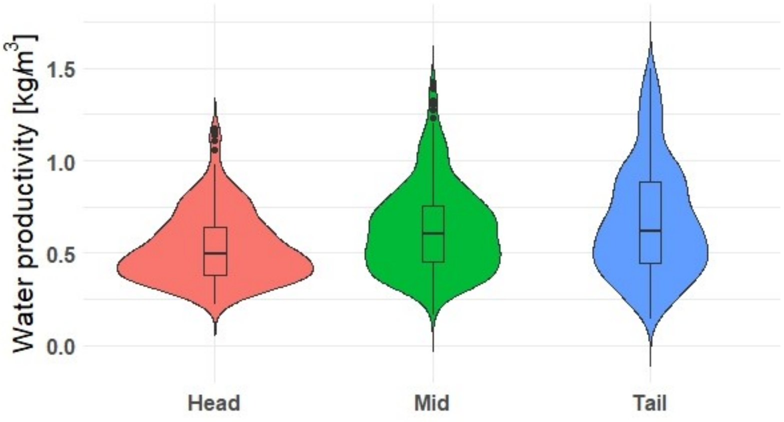

Figure 14: Violin plots of water productivity divided into groups of position in the irrigation scheme with embedded box plots showing median, interquartile range (25th and 75th percentiles) and total range of the data.

Head position differs from mid and tail in median yield and water productivity, while mid position differs slightly from the others in irrigation.

It could be confirmed that yield depends on method of irrigation scheduling, position in irrigation scheme and applied N, through the ANOVA test of the linear regression model, where all variables were highly significant ($p < 10^{-4}$). Interactions did not increase the adjusted R^2 of the model notably and were therefore excluded, the discarded models are discussed in Appendix E. In this model, the slope is determined by the coefficient for N, and the intercept is formed by a combination of the coefficients for the specific irrigation scheduling and position in the irrigation scheme.

The absence of interactions in the model results in the slope being constant regardless of the combination of categorical variables. Further, the coefficient of each categorical variable is independent of the change in the other categorical variable, which is why the significant levels in each category could be studied separately (Table 4). For significant levels of the combinations of categorical data, i.e. irrigation scheduling and position in irrigation scheme, see Appendix F.

The effect of applied N is an estimated yield increase of 6.8 kg per applied kg N, significance level $P < 0.001$ (with a N interval of 20 – 310 kg). All methods except WFD info had significantly different and higher yields than the control group (Table 4), which coincides with the graphical analysis in Figure 9 A. The farmers located in the tail of the irrigation scheme had significantly higher yields than those in head and mid location. The difference between the lowest and highest yield only depending on the irrigation scheduling was 900 kg, an increase of 32 %, while the largest difference obtained depending on position in irrigation scheme was 400 kg, an increase of 13 %.

Table 4: Yield divided first by irrigation scheduling then position. Different superscript indicates significant differences at P < 0.05

Irrigation Scheduling	**Yield (kg ha^{-1})**	**Confidence level of 0.95**
Control	2800^{a}	$^{+100}_{-100}$
WFD	3400^{bc}	$^{+160}_{-160}$
WFD info	2900^{a}	$^{+120}_{-120}$
Chameleon	3700^{c}	$^{+230}_{-230}$
Chameleon info	3200^{b}	$^{+160}_{-160}$

Position	**Yield (kg ha^{-1})**	**Confidence level of 0.95**
Head	3000^{a}	$^{+120}_{-120}$
Mid	3200^{a}	$^{+110}_{-110}$
Tail	3400^{b}	$^{+110}_{-110}$

The estimated means for different combinations of irrigation scheduling and positions are shown in Table 5. Highest yields were achieved by using the Chameleon method in the tail location (3900 kg ha^{-1}), while the lowest yields were obtained for the control group in the head location (2700 kg ha^{-1}). As the model had an adjusted R^2 of 14 %, the estimations cannot be used for predictive purpose, but as indicators of the impact of the different variables. For details of the model see Appendix D.

Table 5: Estimated mean yields in the different combinations of irrigation scheduling and position in irrigation scheme. Confident levels of 0.95 is specified behind estimate. Darker green indicates higher yield

Yield (kg ha^{-1})	Head	Mid	Tail
Control	*2700* $^{+130}_{-130}$	*2800* $^{+120}_{-130}$	*3000* $^{+130}_{-130}$
WFD	*3200* $^{+180}_{-180}$	*3400* $^{+180}_{-180}$	*3600* $^{+180}_{-180}$
WFD info	*2800* $^{+160}_{-160}$	*2900* $^{+140}_{-140}$	*3100* $^{+140}_{-140}$
Chameleon	*3500* $^{+240}_{-240}$	*3700* $^{+240}_{-240}$	*3900* $^{+240}_{-240}$
Chameleon info	*3100* $^{+190}_{-190}$	*3200* $^{+180}_{-180}$	*3400* $^{+170}_{-170}$

In the model for water productivity interactions were also ruled out due to the low gain (< 2 %) in adjusted R^2. The adjusted R^2 of the final model for water productivity was 21 %, for more details see Appendix D. Similarly as for yield all variables tested were included (irrigation scheduling, position in irrigation scheme and applied N) and statistically significant ($p < 10^{-4}$). Since no interactions between the variables were included in this model either, the significant levels for the different factors are again presented separately (Table 6). For significant levels of the combinations of categorical data, i.e. irrigation scheduling and position in irrigation scheme, see Appendix F.

The effect of N was significant and estimated to increase the water productivity with 0.001 kg m^{-3} per applied kg of N (with a N interval of 20 – 310 kg). All irrigation scheduling had significantly higher water productivity than the control group (Table 6), where WDF info has the smallest increase of 0.09 kg m^{-3}. In the violin plot (Figure 11 A) the median water productivity of control and WFD info are similar, but it can be seen that the latter has higher extremes. WFD, Chameleon and Chameleon info were all significantly higher than WFD info, with water productivity ranges of 0.72, 0.81 and 0.73 kg m^{-3}, respectively. Both the mid and tail location had significantly higher water productivity than the head, 0.72 and 0.69 compared to 0.60 kg m^{-3}. The largest difference in water productivity depending on irrigation scheduling was 0.30 kg m^{-3}, an increase of 58 % between the control group and Chameleon.

Table 6: Water productivity divided first by irrigation scheduling then position. Different superscript indicates significant differences at $P < 0.05$

Irrigation Scheduling	**Water Productivity (kg m^{-3})**	**Confidence level of 0.95**
Control	0.51^{a}	$^{+0.02}_{-0.02}$
WFD	0.72^{c}	$^{+0.04}_{-0.04}$
WFD info	0.60^{b}	$^{+0.03}_{-0.03}$
Chameleon	0.81^{c}	$^{+0.06}_{-0.06}$
Chameleon info	0.73^{c}	$^{+0.04}_{-0.04}$

Position	**Water Productivity (kg m^{-3})**	**Confidence level of 0.95**
Head	0.60^{a}	$^{+0.03}_{-0.03}$
Mid	0.69^{b}	$^{+0.03}_{-0.03}$
Tail	0.72^{b}	$^{+0.03}_{-0.03}$

Both the highest and lowest water productivity (0.86 and 0.44 kg m^{-3}) was achieved under the same conditions as the highest and lowest yield, namely in the tail position with the Chameleon technology and the head position for the control group, respectively (Tables 5 and 7).

Table 7: Estimated mean water productivity in the different combinations of irrigation scheduling and position in irrigation scheme. Confident levels of 0.95 is specified behind estimate. Darker green indicates higher water productivity

Water Productivity (kg m^{-3})	Head	Mid	Tail
Control	$0.44\ ^{+0.03}_{-0.03}$	$0.53\ ^{+0.03}_{-0.03}$	$0.56\ ^{+0.03}_{-0.03}$
WFD	$0.65\ ^{+0.05}_{-0.05}$	$0.74\ ^{+0.05}_{-0.05}$	$0.77\ ^{+0.04}_{-0.05}$
WFD info	$0.53\ ^{+0.04}_{-0.04}$	$0.62\ ^{+0.03}_{-0.04}$	$0.65\ ^{+0.04}_{-0.04}$
Chameleon	$0.74\ ^{+0.06}_{-0.06}$	$0.83\ ^{+0.06}_{-0.06}$	$0.86\ ^{+0.06}_{-0.06}$
Chameleon info	$0.65\ ^{+0.05}_{-0.05}$	$0.75\ ^{+0.05}_{-0.05}$	$0.78\ ^{+0.04}_{-0.04}$

5. DISCUSSION

5.1. SOIL PROPERTIES

The similar ranges of FC and PWP in previous studies as well as the Koga Irrigation Database (Table 1) suggest that these values are close to the true FC and PWP in this area. An uncertainty for the bulk density sampled in this study was the problem of getting undisturbed samples from the hard clay soil. Disturbance of these samples would result in lower bulk density. Another possible error is the transfer of samples to oven safe containers where there is a risk of soil loss.

5.2. CALIBRATION OF SOIL MOISTURE PROFILER

The calibration curve established in this study only covers measured values from 4 to 16 % volumetric water content. Extrapolating to cover a larger range would however not be appropriate, and result in unreasonable water contents far above field capacity. The similarities of the two calibration curves found in this study and Hune (2016), respectively, indicate that even though the interval of the two calibration curves is small, there is a relation between the sampled soil moisture and the probe measurements at this interval. As the probes used for these two calibration curves are different, the similarities of the curves also suggest that it might be possible to use the same calibration curve for the different probes. If this is true it would be important for calibrating the measurements from 2018 as it is not known which probe corresponds to each measurement.

An important note is that the measured data used for the calibration curves was cleaned rigorously. With a high presence of errors in between correct measurements, there is a high risk of incorrect measurements having an effect on the calibration. Possible reasons for these errors could be poorly installed access tubes or that the tubes have been negatively affected over time. Air gaps or soil compaction as well as swelling or shrinking of soil with change in water content negatively affect the accuracy of measurements, and are more likely to occur in a heavy clay soil such as in Koga (Delta-T Devices Ltd, 2016). This would explain why all soil moisture probes behaved in a similar way, namely show very low values that corresponds to much higher soil moisture. The probes are also sensitive to changes of salinity in soil exceeding 100 mS m^{-1} (Delta-T Devices Ltd, 2016), according to the top soil data from the Koga Irrigation Database salinity in the area is below 100 mS m^{-1} and should therefore not be an issue (non-saline soil). Another source of error is the soil moisture samples. As the procedure was consistently performed for all samples this error is expected to be systematic, only affecting the vertical position of the curve.

For future measurements, a new calibration should be performed in advance and the access tubes should be reviewed to ensure proper measurements. This would facilitate the direct analysis of results and problematic measurements could be detected on the spot. For the already sampled soil moisture in the database, the calibration curve established using sampled bulk from this study is recommended based on the trade-off between references of bulk density and field capacity (Table 1 and 2). Measurements in the database outside the range of the current calibration curve should not be used unless a new calibration curve extending into wetter and drier soil is produced.

5.3. EVALUATION AND STATISTICAL ANALYSIS OF IRRIGATION SCHEDULING TECHNOLOGIES

The similarities between the slopes of boundary lines (Figure 8) indicate that the black line could represent a boundary function in Koga. Boundary functions provide the highest yield expected for a certain irrigation amount. In Figure 8 many of the points are located far away from the line, indicating that the same yield could be achieved with a lower water input. Points below the line are assumed to be limited by another factor than total amount of water, which also imply large possibilities of improvements in water management as well as other agronomic practices to improve water productivity. One example is nitrogen application, as concluded above. To optimize the yields, further research on the additional factors is needed.

The median yields of WFD, Chameleon and Chameleon info being significantly higher than both the control and previous records suggest a strong positive relationship between yield and the use of these types of irrigation scheduling in Koga. The higher minimum yields for Chameleon could be a result of the timing in irrigation being refined by the technology as well as less leaching of nutrients due to excessive irrigation. A study by Zhang and Oweis (1999) concluded that wheat yield depends not only on total water use during the season, but also timing and precision in critical growth stages. For low-income farmers this could be an important difference and the overall higher yields will make farmers less vulnerable to annual weather variations.

According to the median values, the irrigation amount can be reduced by technologies and information spreading. The cumulative distribution functions for irrigation by groups relying on information from farmers with irrigation scheduling technologies closely followed the same curve as their informers (Figure 10 B), which indicates that information between farmers does have an important effect on irrigation practices. The reduction in irrigation by technologies and shared information did not have a negative effect on yield, which can be explained by over irrigation in the control group as it has been a known issue in Koga (Agide et al., 2016). If the main goal only were to reduce water usage all methods have similar improvements from the control. As higher yields are desirable Chameleon would be preferred before WFD info. An important conclusion is that water productivity could be improved by irrigation scheduling without any setback in yield. With regard to the irrigation sometimes being more than twice the water demand of wheat (Figure 10 A) as well as the comparison with water productivities determined in Pakistan (Hassan, Hussain and Akbar, 2005), there is a large potential of further improvement in water productivity for many of the farmers in Koga (Figure 11 A).

As water productivity is related to yield, similar results were expected among the two linear regression models. It could be concluded, both by the models as well as the comparison of paired means, that all irrigation scheduling methods had a significant effect on yield except WFD info, and water productivity was significantly increased by all irrigation scheduling methods. Although position also had a significant effect on yield, the right type of irrigation scheduling could have a more important effect for the farmers. The underlying reason for differences in position could be more fertile soils or differences in field management, but further investigations are needed to clarify the responsible parameters. As no interactions were included in the model, the effect of nitrogen did not depend on position or irrigation scheduling, and the order of increase by the irrigation scheduling remained the same in all positions. However, a minor interaction effect between type of irrigation scheduling and nitrogen was found, but it was discarded as it did not improve the models coefficient of determination with more than 1 percent.

There are large variations in the results, especially for farmers using Chameleon. The most stable yields were achieved in the control group. A reason for this could be that farmers are not used to Chameleon and interpret the output differently, while the control group is more conform in their management. From the low adjusted R^2-values of the models it can be concluded that other factors than those included do have high importance for the outcome.

It is important to notice that there are sources of uncertainty within the data set used. The sampling of yield was performed by counting 100 kg bags which will include rounding errors. The irrigation was logged by the farmers who clocked their time for irrigation. Different farmers will likely have clocked it differently, some noting the whole time they were working on the field when irrigating, and some noting only the time used when the fields were being irrigated. Another source of uncertainty in the irrigation is that it was assumed that the discharge to the fields always was 0.015 $m^3 s^{-1}$. If there is a difference in discharge between head, mid and tail of the irrigation scheme, this will have an effect on the comparison of irrigation and water productivity depending on location and could explain the differences between them. However, if the assumption that the discharge is consistent throughout the irrigation scheme is correct, a systematic error would only affect the comparison with other sources. A way to minimize this uncertainty would be repeated measurements of discharge in the irrigation scheme throughout the season.

Additionally, there are the risks of misinterpretation or mistyping when entering the hard copies into the database. The large amount of data somewhat makes up for the problems in data collection, but it is important to focus on trends rather than absolute values. Unfortunately, rainfall data for the Koga irrigation scheme was not yet available for this study. Rainfall data from ARARI[2], gathered from 2013 to 2017, is varying between 250 and 800 mm per season, with the majority falling in May and June. Since the planting and harvesting dates could differ with more than a month for different farmers, there is a large difference in water input from rain for crops in different fields. An estimated effect of rainfall would be very uncertain and is therefore not performed in this study. When available, rainfall data from the actual season should be added to the irrigation to get a total water input for each field which would give more comparable results. Furthermore, for a more thorough analysis, several seasons of sampling is recommended.

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[2] Amhara Regional Agricultural Research Institute (ARARI), Adet Agriculture Research Center, Koga irrigation trial site

6. CONCLUSIONS

A calibration curve was established and can be used for the sampled soil moisture measurements of 4 – 16 %. A new calibration is needed for recordings of soil moisture in Koga in the future. Before using the access tubes again they should be reviewed to make sure they are still in a good condition and properly installed. New calibrations are important to facilitate error identification and ensure a correct calibration for each specific measurement device.

This study is further concluding that implementation of irrigation scheduling technologies to a portion of farmers in the irrigation scheme and sharing of their information to neighbors should be a successful approach for improving yield and water productivity in Koga.

All types of irrigation scheduling resulted in lower water usage than the control group, with reductions in median values of 14 – 21 % compared to control. The reduction in irrigation did not show any negative effect on yield. Informed farmers had lower yields than their informers. Chameleon had the largest difference to control, with an average increase in yield of 32 %. More research and understanding, together with improvement of farmer practices in both water management and other agronomic aspects should be the future approach for optimizing yields. Before recommending the irrigation scheduling tools to the farmers in the area, at least one more season of testing should be performed.

It could be concluded that both farmers with irrigation scheduling technologies as well as farmers receiving information from them all had a significantly higher water productivity compared to the control group. Highest effect could be confirmed for Chameleon users (58 % increase compared to control), second highest were Chameleon info and WFD which had similar effects, about 40 % increase. The average water productivity now ranging from 0.5 to 0.8 between the different irrigation scheduling groups still has a large scope of improvement.

Both the position in the irrigation scheme as well as the irrigation scheduling was confirmed to be significantly important for both yield and water productivity. Interaction effects between applied nitrogen and implemented irrigation scheduling were considered insignificant. According to the obtained model, nitrogen application in the used range (20 – 310 kg ha^{-1}) had a linear positive effect on both yield and water productivity (8.6 kg and 0.001 kg ha^{-1} per additional kg applied N, respectively).

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8. APPENDIX

A. MAP OF SOIL MOISTURE SAMPLING SPOTS FOR CALIBRATION

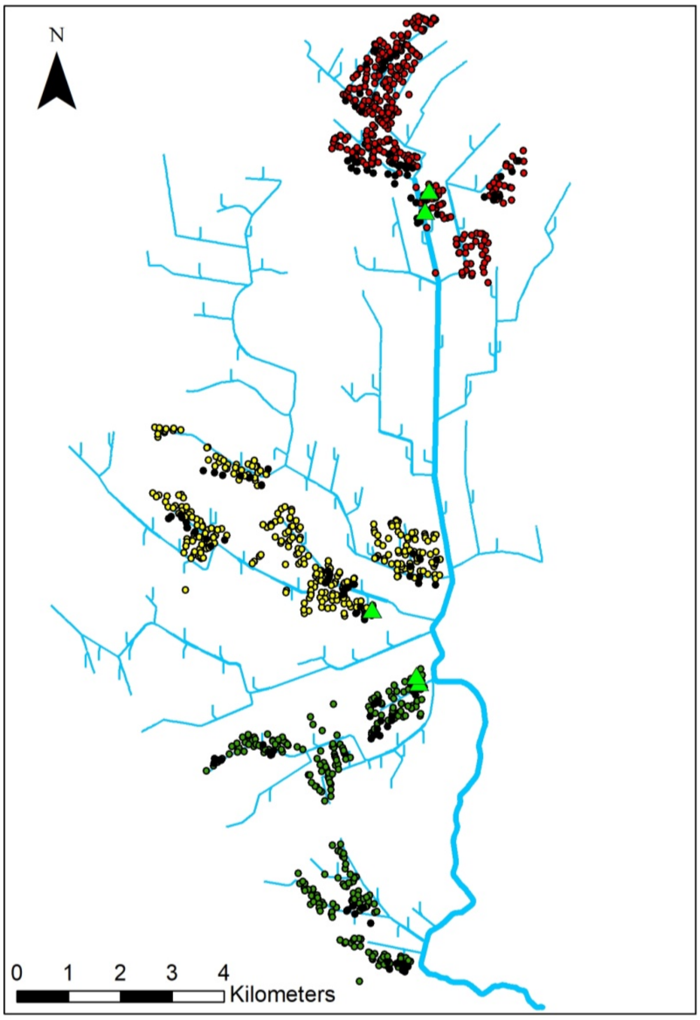


Figure A1: All dots and triangles show the location of a field included in the Koga Database. Black dots and green triangles represent fields with an installed access tube for soil moisture measurements. The green triangles indicate which of the fields with access tubes that were used for soil moisture sampling for the calibration in this study. Blue lines are the canals in the Koga irrigation scheme.

B. DATA CLEANING AND PROCEDURE FOR CREATING CALIBRATION CURVES

The gathered data from the soil moisture sensors was reviewed and all values outside the range of the previously gathered data from 2018 were removed. From the five locations, only the three with the fewest oddities were used. All measurements at the depth of 60 cm were removed as they were far above any reasonable FC (60-90 %).

The obtained values of the volumetric soil moisture content were then plotted against the corresponding measured values for the soil moisture sensor and a linear regression line was calculated. The values from the soil moisture sensor were set on the x-axis as the purpose was to calibrate them, with the sampled soil moisture as the actual soil moisture (y). For comparison, the curve was plotted together with a previously made calibration curve for a different profile probe in the same area.

Additional calibration curves were also created using bulk density values from other research project in the area as a comparison. For this the highest and lowest values from the nearest site were used, and no consideration was taken for the different depths as no such information was given.

C. SCATTER PLOTS

There is an indication of an exponential decay of water productivity with higher irrigation (Figure C1). This relationship is visually enhanced by the rounded values of yield that groups the data points together at certain values. The control group is the most represented in the very high irrigation cases, and this group is not represented at all in the highest water productivity (> 1.2 kg m^{-3}).

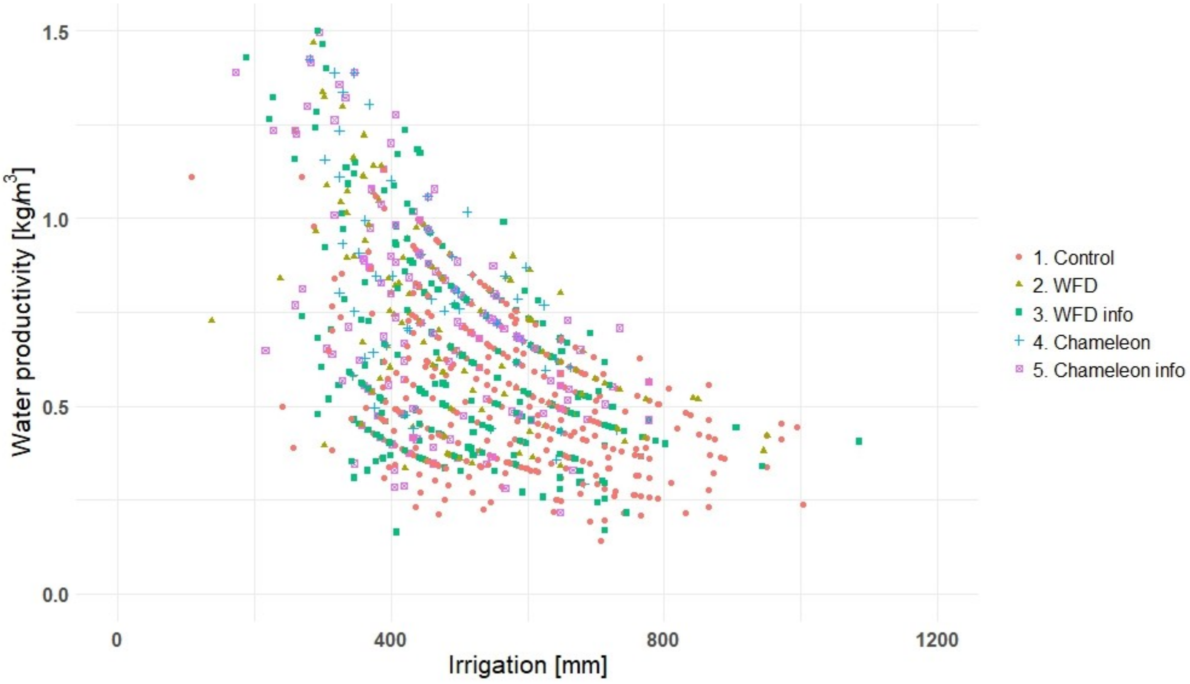


Figure C1: Scatter plot showing the relation between total irrigation and water productivity.

Water productivity is increasing with increasing yield (Figure C2). Here the interpretation of the relationship is also interfered by the rounded values of yield, which makes the data points line up on each other. Taking this problem into account, the majority of data points lie fairly linear with some more extreme highs for the higher yields.

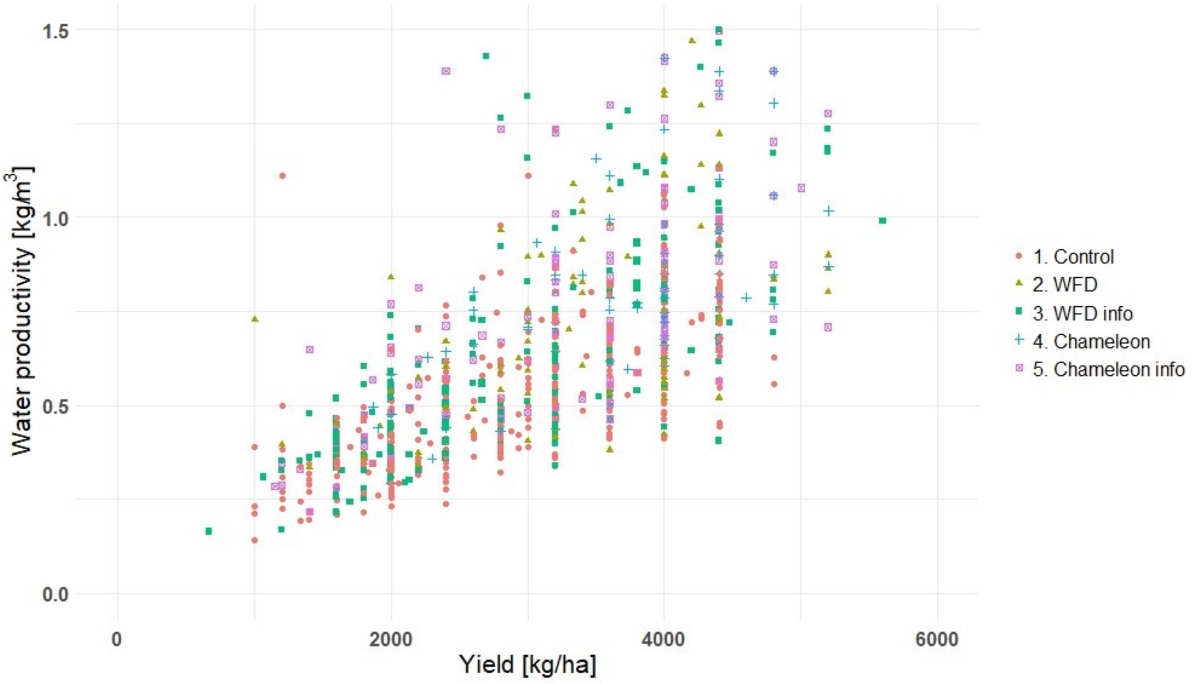
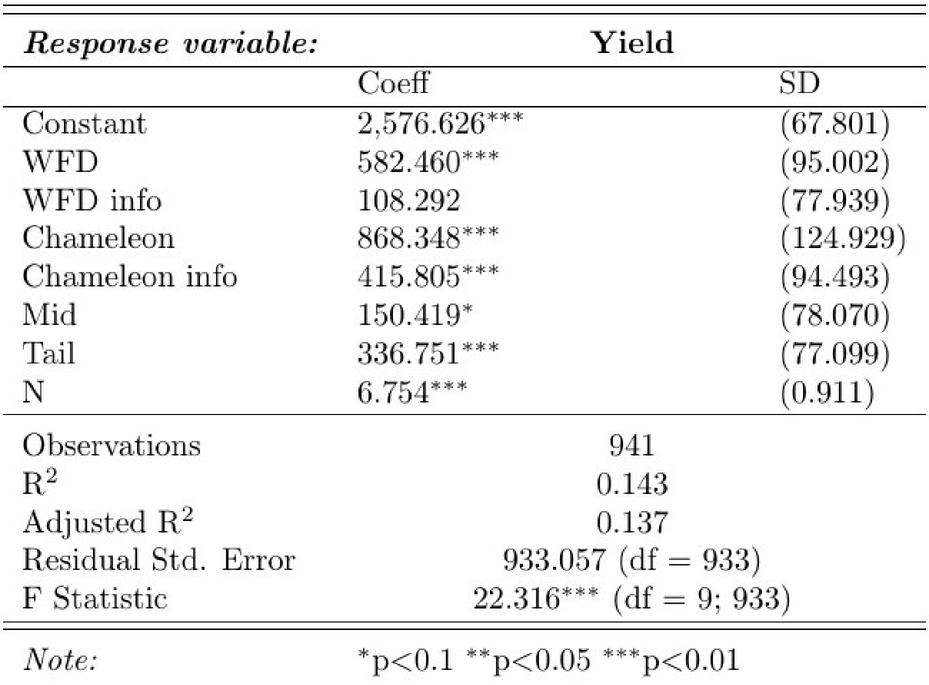


Figure C2: Scatter plot showing the relation between yield and water productivity.

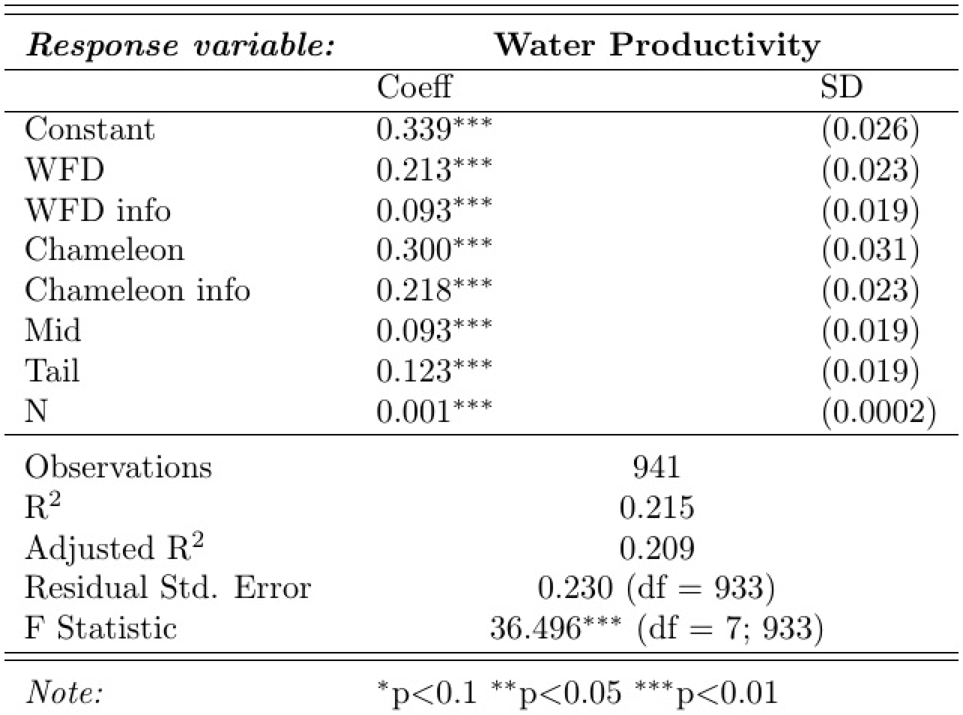
D. SUMMARY OF MULTIPLE LINEAR REGRESSION MODELS

Table D1: Summary of coefficients and statistics of the linear model for yield. The constant assumes control group located in the head of the irrigation scheme.



Response variable:	Yield	
	Coeff	SD
Constant	2,576.626***	(67.801)
WFD	582.460***	(95.002)
WFD info	108.292	(77.939)
Chameleon	868.348***	(124.929)
Chameleon info	415.805***	(94.493)
Mid	150.419*	(78.070)
Tail	336.751***	(77.099)
N	6.754***	(0.911)
Observations	941	
R^2	0.143	
Adjusted R^2	0.137	
Residual Std. Error	933.057 (df = 933)	
F Statistic	22.316*** (df = 9; 933)	
Note:	*p<0.1 **p<0.05 ***p<0.01	

Table D2: Summary of coefficients and statistics of the linear model for water productivity. The constant assumes control group located in the head of the irrigation scheme.



Response variable:	**Water Productivity**	
	Coeff	SD
Constant	0.339***	(0.026)
WFD	0.213***	(0.023)
WFD info	0.093***	(0.019)
Chameleon	0.300***	(0.031)
Chameleon info	0.218***	(0.023)
Mid	0.093***	(0.019)
Tail	0.123***	(0.019)
N	0.001***	(0.0002)
Observations	941	
R^2	0.215	
Adjusted R^2	0.209	
Residual Std. Error	0.230 (df = 933)	
F Statistic	36.496*** (df = 7; 933)	
Note:	*p<0.1 **p<0.05 ***p<0.01	

E. MULTIPLE LINEAR REGRESSON MODELLING

Based on the forward selection method for the multiple linear regression no interactions were included in the final model. During the process, the models in Table D1 were considered.

Table E1: Evaluated models. Asterisk (*) indicates that both main effects and interactions between the variables are included

Yield	**Adjusted R^2**
Pos * N + Meth * N	0.195
Pos * N + Meth	0.189
Pos + Meth * N	0.147
Pos + Meth + N	0.137

WaterProductivity	**Adjusted R^2**
Pos + Meth * N	0.215
Pos + Meth + N	0.209

When using yield as the response variable, the inclusion of the interaction term between position and N lead to an increased goodness-of-fit parameter R^2. However, the best-fit coefficient of the interaction term indicates an unphysical trend of the application of N lowering the yield in some of the positions. Since such behavior seems unreasonable, a model without this interaction term (albeit slightly smaller R^2) was used.

The gain in adjusted R^2 with the inclusion of the interaction between method and N was, both for yield and water productivity as response variable, not sufficient to choose these models over the simpler models without any interactions.

F. YIELD AND WATER PRDOUCTIVITY ESTIMATES FROM MODELS

Table F1: Estimated yields in the different combinations of irrigation scheduling and position in irrigation scheme. Confident levels of 0.95 are specified behind estimate. Darker green indicates higher yield. Different letter behind estimates indicates significant differences at P < 0.05

Yield (kg ha^{-1})	Head	Mid	Tail
Control	$2700a$ $^{+130}_{-130}$	$2800abc$ $^{+120}_{-130}$	$3000bcde$ $^{+130}_{-130}$
WFD	$3200defgh$ $^{+180}_{-180}$	$3400efghij$ $^{+180}_{-180}$	$3600ij$ $^{+180}_{-180}$
WFD info	$2800ab$ $^{+160}_{-160}$	$2900abcd$ $^{+140}_{-140}$	$3100cdefg$ $^{+140}_{-140}$
Chameleon	$3500fghi$ $^{+240}_{-240}$	$3700hij$ $^{+240}_{-240}$	$3900j$ $^{+240}_{-240}$
Chameleon info	$3100bcdef$ $^{+190}_{-190}$	$3200defghi$ $^{+180}_{-180}$	$3400ghij$ $^{+170}_{-170}$

Table F2: Estimated water productivity in the different combinations of irrigation scheduling and position in irrigation scheme. Confident levels of 0.95 are specified behind estimate. Darker green indicates higher water productivity. Different letter behind estimates indicates significant differences at P < 0.05

Water Productivity (kg m^{-3})	Head	Mid	Tail
Control	$0.44a$ $^{+0.03}_{-0.03}$	$0.53b$ $^{+0.03}_{-0.03}$	$0.56bc$ $^{+0.03}_{-0.03}$
WFD	$0.65df$ $^{+0.05}_{-0.05}$	$0.74egh$ $^{+0.05}_{-0.05}$	$0.77egh$ $^{+0.04}_{-0.05}$
WFD info	$0.53b$ $^{+0.04}_{-0.04}$	$0.62cd$ $^{+0.03}_{-0.04}$	$0.65d$ $^{+0.04}_{-0.04}$
Chameleon	$0.74defg$ $^{+0.06}_{-0.06}$	$0.83h$ $^{+0.06}_{-0.06}$	$0.86h$ $^{+0.06}_{-0.06}$
Chameleon info	$0.65de$ $^{+0.05}_{-0.05}$	$0.75fgh$ $^{+0.05}_{-0.05}$	$0.78fgh$ $^{+0.04}_{-0.04}$