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Effect of deficit irrigation and soil fertility management on wheat production and water productivity in the Upper Blue Nile Basin, Ethiopia

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ABSTRACT

In the Ethiopian Upper Blue Nile Basin, like in other regions in the world, agricultural productivity is declining due to water scarcity owing to longer dry seasons coupled with soil acidity−induced fertility problems. Wheat is one of the major food security crops in Ethiopia but its productivity is reduced due to water scarcity, especially during the irrigation season. Addressing these problems might be essential to increase productivity. This study explores the effect of deficit irrigation (DI) combined with lime, manure and inorganic fertilizer on wheat production and water productivity (WP) in the Koga irrigation scheme, Ethiopia. Four levels of DI strategies (100% ETc or 0% deficit as a control, 80%, 60% and 50% ETc) were applied for two irrigated seasons. Five levels of soil fertility management were applied for four consecutive cropping seasons: (i) 0.86 t ha^{-1} lime combined with 3 t ha^{-1} manure and full dose urea and NPS−B (hereafter referred to as inorganic fertilizer) (L3); (ii) 1.15 t ha^{-1} lime combined with 3 t ha^{-1} manure and full-dose inorganic fertilizer (L2); (iii) 1.43 t ha^{-1} lime combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L1); (iv) 3 t ha^{-1} manure combined with full dose inorganic fertilizer (M); and (v) full dose inorganic fertilizer alone (C). The grain yield and biomass data were collected at harvest from a sample area of 2 m × 3 m from each plot with three replicates. The effect of DI and liming, as well as manuring on average grain yield and biomass, were highly significant. Under all irrigation scenarios, higher grain yield and biomass were found at L1, L2, L3 and M (in that order), compared with C. The highest WP was obtained at 50% ETc irrigation dose, compared with 60%, 80% and 100% ETc (in that order). Yet, the lowest WP was found at C under all irrigation scenarios compared with L1, L2, L3 and M. The WP increased when the amount of water supply decreased and liming doses increased. The application of full dose lime and manure combined with 50% ETc DI resulted in comparable grain yield, biomass and WP as 100% ETc full irrigation at L3 and M. It could be concluded that liming and manuring could be used to mitigate the yield penalty effect of DI in the study area. In scenarios where farmers have to pay for water, profitability rises as the irrigation water supply reduces. Thus, under such conditions, a 50% ETc irrigation scenario is more profitable than scenarios with 60%, 80% and 100% ETc irrigation.

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1. Introduction

Wheat (*Triticum aestivum* L.), the target crop in this study, is one of the world's most important food crops, yielding an average of 3 t ha^{-1} globally (Ali et al., 2019; Anon, 2016, 2013; Yu et al., 2020). In Ethiopia, the average wheat yields grew from 1.3 t ha^{-1} in 1994 (CSA, 1995) to 2.5 t ha^{-1} in 2021 (CSA, 2021). But, the demand for wheat has grown-up substantially over the past decades and is expected to continue (Tadesse et al., 2022; Hordofa et al., 2022; Hodson et al., 2020; Mann and Warner, 2017). The current wheat production is inadequate to meet the national demand, forcing the country to import 30–50% to fill the gap (Hodson et al., 2020; Shikur, 2022; Minot et al., 2015). Though wheat is widely grown in Ethiopia, its productivity is low mostly due to soil fertility depletion as a result of continuous crop nutrient uptake, soil acidity-induced fertility problems, inadequate use of fertilizer, insufficient organic matter application and crop failure due to moisture stress (Gurmessa, 2020; Agegnehu et al., 2019; Agegnehu and Yirga, 2009). Yield gap analysis has shown that improved soil and water management practices, including increased fertilizer use, proper soil fertility maintenance and irrigation, have the potential to increase production (Hordofa et al., 2022; Hodson et al., 2020; Taye et al., 2020b; Mann and Warner, 2017).

Soil acidity substantially affects ~50% of the world's potentially arable soils (Demil et al., 2020; Hodson et al., 2020; Tefera et al., 2022; Kochian et al., 2004). In the high rainfall areas of Ethiopia, ~43% of the cultivated land is affected by soil acidity (Taye et al., 2020a), and more than 80% of the Nitisols are acidic (Demil et al., 2020; Agegnehu et al., 2019). The problem is most serious in northwestern Ethiopia (where this study was conducted), and in the country's central and southwestern highlands (Demil et al., 2020; Taye et al., 2020b; Tefera et al., 2022; Haile and Boke, 2011). High rainfall-induced leaching, acidic parent materials, removal of organic matter and continuous application of acid-forming fertilizers are some of the major causes of soil acidity (Taye et al., 2020b; Tefera et al., 2022; Agegnehu et al., 2019; Haynes and Naidu, 1998).

Soil acidity hampers microorganism activity, reduces plant root growth, and restricts the absorption of nutrients and water movement (Taye et al., 2020b; Tefera et al., 2022; Abate et al., 2013). The availability of micronutrients such as aluminum, manganese and iron increases as the pH decreases (Agegnehu et al., 2019). Crops planted in acidic soils can be stunted, are vulnerable to drought and are not very responsive to fertilizers, which eventually leads to low productivity (Taye et al., 2020b; Abate et al., 2013). In response to this, farmers tend to apply higher rates of fertilizer than the recommended dose (Tefera et al., 2022; Tamene et al., 2017). Asmamaw et al. (2021a) confirmed that in Koga, located in northwestern Ethiopia, the fertilizer response of the crop is declining. Unless due attention is given to the amendment and maintenance of soil acidity, it can lead to a decline or complete failure of crop production (Agegnehu et al., 2019). This attention is needed given that the soil acidity problem in Ethiopia is mainly found in the high crop production potential areas of the country (Taye et al., 2020b; Tefera et al., 2022; Dinkecha, 2017).

Several authors found that soil acidity can be managed using integrated soil fertility management (ISFM) practices such as lime, manure, crop residue, inorganic fertilizers and biochar application (Abate et al., 2013; Ameyu, 2019; Asmare and Markku, 2016). Worth noting is that the application of organic matter in the form of manure and compost can reduce soil acidity (Tefera et al., 2022; Mike, 2003). Thus, applying organic manure seems a good strategy for the resource-poor farmers of the tropics who cannot afford a large volume of lime and inorganic fertilizers (Taye et al., 2020a; Abate et al., 2013; Agegnehu et al., 2014).

Coupled with soil acidity−induced fertility problems, water scarcity during the extended dry season is the major limiting factor for agricultural production in Ethiopia (Asmamaw et al., 2021a, 2021b). To curb this problem, farmers apply small−scale irrigation by river diversion and groundwater pumping, but their application system often results in doses being either more or less than the crop water requirements (Beyene et al., 2018). Over−irrigation increases the cost of production and might leach nutrients out of the root zone. Yet, introducing an efficient irrigation water management strategy such as deficit irrigation (DI) is important for farmers (Asmamaw et al., 2021b). Hence, there is a growing interest in DI, an irrigation practice whereby water supply is reduced below maximum and mild stress is allowed with minimal effects on yield, thus leading to higher water productivity (WP) (Abdelhady et al., 2017; Ali et al., 2019; Flörke et al., 2018; Gahnnem et al., 2021; Yu et al., 2020; Geerts and Raes, 2009).

In a recent review in Ethiopia, Asmamaw et al. (2021b) showed that for saving 65% water, the yield penalty was 26%, while WP increased by 110% for wheat. In addition, by irrigating less water per unit area, the area under irrigation could be expanded. To keep yield levels high, combining DI with soil acidity management activities such as liming and manuring, combined with inorganic fertilizer, might be needed. Yet, scientific studies that combine DI with ISFM under wheat production are not available (Asmamaw et al., 2022).

In Koga, there are poor, medium and rich farmers (Asmamaw et al., 2021a). By considering farmer's lime purchasing power, searching for applicable alternative acidic soil management options is essential. To identify cost−effective ISFM strategies, analyzing revenue and gross profit for these strategies is also imperative. Combining ISFM with improved irrigation strategies could reduce water scarcity and improve crop productivity. Designing efficient deficit irrigation options could reduce pressure on water resources and increase the area under irrigation. Hence, understanding the possible effect of DI and ISFM on grain yield, biomass and WP is vital. To bridge these knowledge gaps, the effect of lime at different rates, with fixed doses of manure and inorganic fertilizer combined with DI on wheat production and WP was evaluated. The specific objectives of this study were: (i) to evaluate the effect of DI and ISFM including applications of lime combined with manure on wheat grain yield and biomass; (ii) to assess the combined effect of DI and ISFM on WP compared with the use of inorganic fertilizer and full irrigation; (iii) to identify cost−effective irrigation and ISFM strategies.

The effects of liming and manuring on physical, chemical and biological quality of the acid soils under study have been reported elsewhere.

2. Materials and methods

2.1. Description of the study site

The field tests were carried out in Ethiopia part of the Upper Blue Nile basin at Koga irrigation scheme (12°61′23" N and 37°03′ 92" E) in 2018/19 and 2019/20 irrigated seasons. The experimental site has an average slope of less than 0.2%. The long-term (1987–2020) meteorological data collected from Ethiopian National Meteorological Service Agency's Bahir Dar branch revealed a rainfall distribution with a unimodal pattern (Asmamaw et al., 2021a). The yearly rainfall ranges from 855 to 2200 mm with a mean of 1528 mm. The highest air temperatures and reference evapotranspiration (ETo, mm) are recorded in March and April, while the lowest air temperatures and ETo are recorded in January and December, and July and August, respectively (Supplementary Fig. S1).

The season for irrigated wheat normally begins in October, when rainfall drops significantly, and lasts until January, while the irrigated maize season begins in January and ends in May. Supplmentary Table S1 shows the monthly meteorological information for the 2018/19 and 2019/20 irrigated wheat growing seasons, including rainfall (mm), maximum and minimum air temperatures (°C), relative humidity (%), sunlight hours (h day^{-1}), and wind speed (m s^{-1}, recorded at 2 m height). In contrast to the long-term trend (Supplementary Fig. S1), neither 2018/19 nor 2019/20 experienced any rain from October to January.

Based on Asmamaw et al. (2022) report, the soils of the study area are clayey and categorized as Nitisols (WRB, 2015). The soils have a very low sand content (2.6%) compared to a very high clay content (72%), Supplmentary Table S7. Also, relatively higher dry bulk density was found in both soil depths. In comparison to the control, liming doses combined with manuring improved bulk density which improved moisture content at field capacity.

The average soil pH (H_2O) at the control plot was 5.15 (Asmamaw et al., 2022). The soil exchangeable acidity was considerably high. However, the sodium adsorption ratio was low. Thus, soil condition in Koga is strogly acidic (Asmamaw et al., 2022). Daily ETo was calculated by the CropWat program based on the FAO Penman–Monteith equation (Smith et al., 1998). The electrical conductivity of the irrigation water was 0.90 dS m^{-1} (Asmamaw et al., 2022).

2.2. Experimental design

Experiments were done under deficit irrigation (DI), for four successive irrigated seasons (2018/19–2019/20). In this study, the annual cropping sequence was wheat (*Triticum aestivum* L.) - maize (*Zea mays* L), with wheat grown in the first round of the irrigation season (October to January) and maize during the second round of the irrigation season (January to May) similar to farmer's practice in Koga. Only the findings for wheat are presented here.

To exactly apply farmers' practices such as ploughing, furrow preparations, weed and pest control, ten model farmers were involved during the experiments (i.e. five farmers per year). Because of other farmers' interest to be involved in our research, those who were involved in 2018/19 were substituted by another new five farmers. They worked together in the same field based on the researcher's instructions. The field management practices (ploughing and weed management) were the same except for the deficit irrigation (DI) and integrated soil fertility management (ISFM) treatments. Field managements were done on the same day. Trainings were given to the participating farmers on the main concepts and application of lime ($CaCO_3$) and manure combined with inorganic fertilizer and DI.

The effect of ISFM and DI treatments was tested in a full factorial experiment with five ISFM and four irrigation water scenarios yielding 20 treatments (5 *4) and with three replicates. The treatments were randomly arranged in three blocks. Each block contained a complete replicate of the treatment setting (Supplementary Fig. S2 shows 1 block). Except for the treatments, the other possible factors such as soil conditions, field management (ploughing, weed and pest control), slope (land leveling), plot sizes, plot shape and furrow length were the same in all plots. Thus, ISFM treatments with three levels of lime, a fixed level of manure and inorganic fertilizer were arranged in a randomized complete block design.

The ISFM treatments were (i) 0.86 t ha^{-1} lime (60% of the lime requirement) combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L3); (ii) 1.15 t ha^{-1} lime (80% of lime requirement) combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L2); (iii) 1.43 t ha^{-1} lime (100% of lime requirement) combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L1); (iv) 3 t ha^{-1} manure combined with full dose inorganic fertilizers (M); and (v) full dose inorganic fertilizer (C) as a control (Supplementary Table S2).

Three water stress scenarios (80% ETc, 60% ETc and 50% ETc) and a full irrigation (100% ETc) treatment were defined because, in agricultural real life, farmers have experienced limited water availability during the dry season. Full irrigation (100% ETc estimated by CropWat) was used as a control for DI scenarios.

2.3. Soil fertility management

The manure was prepared from cow, sheep, poultry and pig dung by the researcher. It was stored in a room for a few days, packed in sacks and stored in a room for a month until application.

Based on its local availability and the current level of soil acidity, 3 t ha^{-1} of manure was applied. Farmers manually broadcasted and thoroughly mixed it into the soil while working in dry weather using an ox-driven *Maresha plough* to till the soil to a depth of 10–15 cm on the same dates (Asmamaw et al., 2012; Temesgen et al., 2012).

Based on the advice of the Ethiopian Institute of Agricultural Research, the required amount of lime was calculated (Agegnehu et al., 2019). The estimate takes into account the soil's bulk density, depth of tillage, degree of exchangeable acidity, and pH. Similar to the manure, a month before planting, the lime was mixed into the soil to a depth of 10–15 cm.

Mineral fertilizer comprised urea (46% N) and NPS–B (nitrogen, phosphorus, sulphur and boron). For all treatments, a full dose of urea (183 kg ha^{-1}) was used, and the dose was determined in accordance with the Amhara Region Agricultural Research Institute's recommendation (ARARI, 2014). During sowing, 1/3 of the urea was administered, and the remaining 2/3 was applied while the wheat was at the tillering stage. NPS-B, which contains 18.9% nitrogen, 37.7% phosphorus, 6.95% sulfur, and 0.1% boron, was applied at a full dose (120 kg ha^{-1}).

2.4. Crop water requirement and irrigation scheduling

Daily ETo was computed using the CropWat program version 8.0 based on the FAO Penman-Monteith equation as described by Allen et al. (1998). The daily weather data was collected from the Bahir Dar meteorological station, 35 km north of the study site. In addition, daily rainfall and temperature data were recorded using a tipping bucket rain gauge (HOBO Ware, equipped with a data logger) and a thermometer installed at the study site, and used as input for irrigation scheduling.

Optimum soil moisture depletion level and root depth were adopted from FAO Irrigation and Drainage Paper 56 (Allen et al., 2006). The crop coefficient (Kc) for wheat (kekeba variety, similar to our tested crop variety) was adopted from Tezera et al. (2019). They studied wheat seasonal water demand and crop coefficient for three succeeding years following standard procedures as part of the Ethiopian Institute of Agricultural Research trials. The daily water requirement of the crop and actual evapotranspiration (ETc) was calculated using the CropWat program version 8.0 as well. The ETc and Kc values are lowest, highest and moderate at the initial, mid and late stages, respectively (Supplementary Table S3).

2.5. Irrigation water management

In the scenario analysis, we evaluated the effect of reducing the net irrigation requirement (100% ETc) by 50%, 40%, 20%, and 0% during the whole growth stages of wheat. A rain-fed scenario with no irrigation was not evaluated as this typically results in complete crop failure. The watering was scheduled rotationally, as the experimental site is part of the Koga irrigation scheme, where more than 10,000 households are benefiting from the same water source (Koga dam). All plots were commonly off-season irrigated with 30 mm of water two days before sowing as pre-irrigation (i.e. the sowing dates were 28 September for 2018 and 2 October for 2019). The crop was irrigated every 12 days using the furrow irrigation method, totaling the number of irrigation events to 8 per growing season. Supplementary Table S3 shows the irrigation scheduling for all treatments.

A 15-cm (6-inch) throat width calibrated standard Parshall flume installed at the inlet of the main plot was used to measure the discharge (Supplementary Fig. S3). Water was diverted into the experimental field from a quaternary canal at a constant discharge rate. This discharge was allowed to flow into a plot and each furrow for a given time. The time, t (s), required to apply the desired depth of water was calculated as:

$$t = \frac{DA}{Q} \tag{1}$$

where D is the depth of water to be irrigated in every irrigation session (m), A is the plot size to be irrigated (m^2) and Q is the discharge ($m^3 s^{-1}$). Instantly after the desired depth was applied to a given plot, the discharge was cut-off by closing the channel banks to stop water from entering the plots. The discharge, Q, was estimated as:

$$Q = KH_a^n \quad (2)$$

K is the flume discharge constant (coefficient) which varies with throat width/ flume size, H_a is the depth at the point of measurement (m), and n is the discharge exponent (depends upon flume size).

2.6. Crop management

Wheat (*Triticum aestivum* L.) kekeba variety (*Picaflora #1)* was planted for two irrigated seasons with wheat-maize cropping sequences. Kekeba, a bread wheat variety is a semi-dwarf, is early maturing and is widely cultivated in various parts of Ethiopia. It can grow under a wide range of agro-ecological conditions, ranging from an altitude of 1500–2200 m a.s.l. (Mahamed et al., 2011). Sowing was done by drilling manually in a row after the land was well prepared (four tillage passes) with a seeding rate of 150 kg ha^{-1} on 28 September 2018 and 02 October 2019. The seed was sown in a double row on both sides of the ridges. Weed management was done manually every season. The crop was harvested on 26 January 2019 and 01 February 2020, in the 2018 and 2019 irrigated seasons, respectively.

2.7. Soil moisture data collection

By considering the wheat root zone, gravimetric soil water content was measured one day before and two days after each irrigation session at depths of 0–20, 20–40 and 40–60 cm with three replicates in each treatment. Samples were taken at different spots of each plot for every irrigation events during the study periods (2018/19 and 2019/20). The mean soil water content in the soil profile was taken to be the average of the soil water content measured in the 0–60 cm soil layer. Soil samples were collected using 10 cm height core samplers and the samples were oven-dried at 105 ^{0}C for 48 h and the water content in the soil was determined on a weighted base as follows:

$$\theta_m = \frac{(w_w - w_d)}{w_d} x100 \quad (3)$$

where θ_m is water content on a weight basis (%), w_d is weight of dry soil (g), and w_w is weight of wet soil (g).

But, for ET water productivity calculations, the soil water content only taken at plantig and ripening periods was considered.

2.8. Crop data collection and yield calculation

Plant height was measured at the maturity stage in each plot with three replicates. For all plant samples, data were collected from the middle rows. The grain yield and aboveground biomass data were collected at harvesting time from a sample area of 2 m × 3 m in each plot with three replicates and the average values were taken for statistical analysis for all treatments. The harvested crop was sun-dried and threshed separately using wooden sticks and finally, the grain was separated, cleaned and weighed to record the grain yield. The weight of a thousand grains per plot was recorded by 3 decimal places using a sensitive weighing balance with three replicates.

Grain yield was measured as the weight of harvested grain and adjusted to 13.5% standard moisture content for wheat (Meskelu et al., 2017). It was then converted to tons per hectare. It was also expressed per amount of irrigation water that would be needed to meet the net irrigation water requirement (NIW). This allowed us to assess the yield that can be produced under DI when using the same amount of water as with full irrigation, but on land currently not irrigated as well.

Yield per total NIW was calculated by multiplying the yield observed per ha for a given ISFM treatment with a factor of 1.23, 1.58 and 1.85 for 80%, 60% and 50% ETc DI strategies, respectively. These values were obtained by dividing total net irrigation water (NIW) by total applied irrigation water (AIW) (Supplementary Table S3), including the 30 mm pre-irrigation water. Under full lime treated treatment (L1), for example, if the yield is 5.4 t ha^{-1} at full irrigation with 378 mm of water, then, under 100% ETc, yield per total NIW is indeed 5.4 t, while, under 80%, 60% and 50% ETc it is 6.4, 8.1 and 8.9 t, respectively, for the same 378 mm water for 2018 season (Table 2). The area under irrigation needed to produce these yields is then 1 ha for full irrigation, and 1.23, 1.58 and 1.85 ha for DI strategies, respectively. On land that is not irrigated, there is no yield given the lack or complete absence of rain between October and January.

2.9. Water productivity

Crop water productivity (*WP*) was calculated to evaluate the effects of DI strategies as:

$$WP = \frac{Y}{ET} \quad (4)$$

where Y is the marketable wheat grain yield (kg), and ET is the seasonal (total) evapotranspiration (mm) estimated by the water balance equation (Du et al., 2015):

$$ET = P + I + C + (SW_1 - SW_2) - D - R \quad (5)$$

where P (mm) is the total rainfall; I (mm) is the amount of irrigation water; C (mm) is capillary rise into the root zone; SW_1 (mm) is the soil moisture content at planting time, SW_2 (mm) is the soil moisture contents at late ripening stage; D (mm) is the drainage; R (mm) is the surface runoff.

The groundwater table measured from two piezometers remained below 5 m depth, while the capillary rise was estimated at 1.1 m using the AquaCrop model. We, therefore, assumed that there was no upward flow that contributed to the root zone. The study field was flat ($<$0.2% average slope) so a runoff was never observed and also we used end diked furrows. Deep percolation (drainage) was negligible since the amount of irrigation water was equal to the depletion amount in the root zone. Thus, the applied irrigation water was aimed to replenish the soil to field capacity.

2.10. Gross profit analysis

To assess and compare the short-term economic returns of producing wheat using DI under ISFM strategies, a rough gross profit analysis was done. Such analysis is imperative to provide an applicable recommendation to farmers and farm managers. The gross profit was computed as (Kifuko et al., 2007):

$$\text{Gross profit} = \text{Revenue} - \text{input costs} \quad (6)$$

$$\text{Revenue} = \text{Grain yield} \times \text{market price} \quad (7)$$

Input costs and revenue of wheat cultivation in the study area are summarized in Table 3. The unit cost was calculated based on existing retail prices during the study periods. Labor costs included sowing, watering, fertilizer application, weeding, manuring, liming, harvesting and shelling costs. The data used for labor cost analysis was recorded at the specific time of each activity within the season. Computations were based on the existing labor cost for daily workers and the number of days required to realize a given activity. Wheat yield was computed as an average per treatment for the two seasons. Revenue from wheat grain yield was computed using existing market prices in Koga.

Input costs, revenue and gross profit were calculated per ha and per total NIW applied. The additional land that could be irrigated using the saved water due to deficit irrigation, as well as the extra costs associated

Table 2
Grain yield per total applied irrigation water amount as affected by deficit irrigation under integrated soil fertility management strategies in the 2018/19 and 2019/20 irrigated seasons. These values are calculated from Table 5.

DI treatment	ISFM treatment 2018/19					ISFM treatment 2019/20				
	L1	L2	L3	M	C	L1	L2	L3	M	C
100% ETc	5.4	5.1	4.9	4.6	3.2	5.6	5.2	5.1	4.8	3.3
80% ETc	6.4	6.0	7.5	5.7	3.6	6.6	6.3	5.8	5.7	3.8
60% ETc	8.1	7.6	7.4	7.1	4.0	8.5	7.7	7.3	7.3	4.7
50% ETc	8.9	8.5	7.3	8.1	4.4	9.4	8.7	8.5	8.3	5.4

Note:100% ETc = full irrigated; 80% ETc = 80% ETc applied; 60% ETc = 60% ETc applied; 50% ETc = 50% ETc applied. DI = deficit irrigation. ISFM = integrated soil fertility management

Table 3
Total input cost, revenue and gross profit averaged over two seasons (2018/19 and 2019/20) per hectare and per total irrigated water amount (AIW) or equaling the net irrigation water requirement (NIW).

DI treatment	Input cost (US$ ha^{-1})					Input cost (US$ per AIW)				
	L1	L2	L3	M	C	L1	L2	L3	M	C
100%ETc	513	455	395	215	180	514	455	395	215	180
80%ETc	513	455	395	215	180	632	560	486	264	221
60%ETc	513	455	395	215	180	812	719	624	340	284
50%ETc	513	455	395	215	180	951	842	731	398	333
	Revenue (US$ ha^{-1})					Revenue (US$ per AIW)				
100%ETc	2145	2028	1950	1833	1287	2145	2028	1950	1833	1287
80%ETc	2067	2028	1833	1794	1170	2633	2477	2223	2262	1560
60%ETc	2028	1911	1794	1755	1092	3374	2691	3081	2906	2009
50%ETc	1950	1833	1755	1755	1053	3978	3705	3608	3393	2340
	Gross profit (US$ ha^{-1})					Gross profit (US$ per AIW)				
100%ETc	1631	1573	1555	1618	1106	1631	1554	1555	1618	1106
80%ETc	1554	1573	1438	1579	990	2001	1917	1913	1998	1339
60%ETc	1515	1456	1399	1540	912	2562	2460	2457	2566	1725
50%ETc	1437	1400	1360	1540	873	3027	2863	2877	2995	2007

Note: 100% ETc = full irrigated; 80% ETc = 80% ETc applied; 60% ETc = 60% ETc applied; 50% ETc = 50% ETc applied. AIW = applied total irrigation water amount. For L1, L2, L3, M and C as in Supplementary Table S2

with cultivating additional land (fertilizer, seed, labor, lime, manure and other charges) were then taken into account (Supplementary Table S4).

2.11. *Statistical analyses*

Statistical analysis and graphics were done in R software, version 3.4.2. (R development core team, 2020). The effect of DI and ISFM treatments on wheat grain yield, biomass, plant height and thousand-grain weight were analyzed through randomized complete block design using a two-way analysis of variance (ANOVA) with replications following the General Linear Model procedure. Tukey (HSD) multiple comparisions test was used for mean separation when the analysis of variance showed statistically significant differences ($P < 0.05$) between the parameters. The relationships between yield and thousand-grain weight, biomass and plant height, water productivity and applied water were analyzed by linear regression. The residual normal distribution and homoscedasticity of the data were tested before these analyses.

Table 1
Mean grain yield per unit of land (t ha^{-1}) as affected by deficit irrigation under ISFM strategies in the 2018 and 2019 irrigated seasons.

DI treatment	Irrigated Season	ISFM treatment				
		L1	L2	L3	M	C
100% ETc	2018	5.4 (0.3)^{Aa}	5.1 (0.4)^{Ab}	4.9 (0.1)^{Ac}	4.6 (0.2)^{Bd}	3.2 (0.2)^{Ae}
	2019	5.6 (0.1)^{Aa}	5.2 (0.2)^{Ab}	5.1 (0.2)^{Ab}	4.8 (0.2)^{Ac}	3.3 (0.2)^{Ae}
80% ETc	2018	5.2 (0.2)^{Bb}	4.9 (0.4)^{Bc}	4.7 (0.2^{Bd}	4.6 (0.2)^{Bd}	2.9 (0.1)^{Be}
	2019	5.4 (0.1)^{Ba}	5.1 (0.1)^{Bb}	4.7 (0.1)^{Bc}	4.6 (0.1)^{Bd}	3.1 (0.1)^{Be}
60% ETc	2018	5.1 (0.2)^{Ca}	4.8 (0.1)^{Cb}	4.6 (0.2)^{Cc}	4.5 (0.2)^{Bc}	2.5 (0.2)^{Ce}
	2019	5.4 (0.2)^{Ba}	4.9 (0.2)^{Cb}	4.6 (0.1)^{Cc}	4.6 (0.2)^{Bc}	3.0 (0.3)^{Cf}
50% ETc	2018	4.8 (0.2)^{Da}	4.6 (0.2)^{Db}	4.5 (0.1)^{Db}	4.4 (0.2)^{Cc}	2.4 (0.1)^{De}
	2019	5.1 (0.1)^{Ca}	4.7 (0.2)^{Db}	4.6 (0.1)^{Db}	4.5 (0.2)^{Cc}	2.9 (0.2)^{Df}

The standard deviation of the mean value is given in parentheses. Values in a column followed by the same capital letters are not significantly different ($p < 0.05$) between the DI treatment (ETc%) for each ISFM, while values in a row followed by the same small letters are not significantly different between the ISFM treatment for each DI (ETc%). 100% ETc = full irrigated; 80% ETc = 80% ETc applied; 60% ETc = 60% ETc applied; 50% ETc = 50% ETc applied. L1, L2, L3, M and C as in Table 2.

3. Results

3.1. *Grain yield per ha of land*

Table 1 shows the treatments' effect on wheat grain yield per ha for the irrigated seasons of 2018/19 and 2019/20. Under all treatments, there was no statistical difference in grain yield among treatments between the 2018/19 and 2019/20 experiment seasons except for that under DI strategies at C. Yet, there was a slight yield increase in 2019/20 for most ISFM treatments (L1, L2, L3 and M).

Grain yield per ha was significantly ($p < 0.05$) affected by water deficits regardless of the soil fertility levels (Table 1 and Suplementary Table S11). The Tukey (HSD) multiple mean comparision test proved that all DI scenarios were significantly different (Suplementary Table S12). At 80% ETc DI, it was reduced by 2.0–8.0% under L1 to L3, by 0–4.2% under M and by 6.1–9.4% under C in comparison with 100% ETc full irrigation. When DI was 60% ETc, grain yield under L1 to L3 was

4.0–10% lower than that at full irrigation, while under M this was 2.2–4.2% and under C 9.1–22%. A 50% ETc DI resulted in a reduction in grain yield of 8.2–11% under L1 to L3, of 4.3–6.3% under M and 12–25% under C.

Irrespective of the irrigation water doses, the ISFM application rate considerably ($p < 0.05$) affected the grain yield per ha (Table 1 and Suplementary Table S10). The Tukey (HSD) multiple mean comparision test results also confirmed that all ISFM treatments were significantly different (Suplementary Table S13). The grain yield was improved by 52–104% under the lime combined with manure treatments (L1 to L3) and by 44–80% under M compared with C under all irrigation strategies (100–50% ETc).

When looking at the interaction between DI and ISFM, it was also statistically significant ($p < 0.05$) (Supplementary Table S6). This suggests that, in addition to the individual significant effects of DI and ISFM, their synergy had a significant impact on wheat yield. The control treatment (C) significantly different with the other combined DI and ISFM tratments in both study years (Supplementary Table S6). Full lime dose (L1) was highly significant compared with L3, M and C under all irrigation scenarios in 2018 irrigated season. When considering only 2019 irrigated season, L1 and L2 were significantly different compared with L3 and M. But, M and L3 are not significant under all irrigation scenarios. Compared with L1 at 60% and 50% ETc, L2 at 80% and 60% ETc was not significantly different.

The positive effect of soil fertility improvement through liming and manuring combined with inorganic fertilizers on wheat yield was significantly decreased with decreasing water stress. But, as presented in Table 1, liming and manuring significantly improved wheat yield under non-limited water supply conditions, and this effect decreases with reducing water supply. With soil fertility stress circumstances, the beneficial impact of optimal moisture availability on wheat yield was significantly reduced. But, the full irrigation combined with improved soil fertility levels siginificantly increased wheat yield.

Yield penalties resulting from reduced irrigation were affected by lime dose, with higher lime doses (L1) showing relatively the lowest yield penalties and lower lime doses (L3) the largest. Interestingly, at M (no lime applied), the grain yield reduction was smaller than under lime and manure (L1-L3), while the highest reductions were observed under C. The positive response to ISFM was least pronounced under full irrigation and became higher with less water being applied. For example, the increase from C to L1 (highest increase among ISFM treatments) was 69–70% at 100% ETc, while at 60% and 50% ETc it varied between 76% and 104%, depending on the year. The 80% ETc treatment took an intermediate position. Similar observations can be made for the other ISFM treatments.

Worth noting is also, particularly as all treatments received inorganic fertilizer at recommended rates, e.g. at 50% ETc DI, the grain yield per ha under L1 was only 0–2% lower than that under M and higher than that under L3 (4–6%) when both received (100% ETc) full irrigation. The use of 50% ETc DI under M yielded even a 36–38% higher grain yield per ha compared with full irrigation under C.

3.2. Biomass, plant height and thousand–grain weight

The effect of irrigation water regimes and soil fertility conditions on biomass was highly significant ($p < 0.05$) in both seasons (Supplementary Table S8). The trends observed are similar to those of grain yield, though the differences in response between liming (L1 to L3), M and C seem less pronounced than was the case with grain yield. Compared with full irrigation, the biomass reduction was 1.5%– 20% under L1 to L3, 12–20% under M and 13–21% under C at 80%, 60% and 50% ETc DI strategies. As for yield, we only see minor differences in biomass between 2018/19 and 2019/20. But, whereas for yield the minor differences always resulted in higher yields in 2019 as compared to 2018, this was not the case for biomass where minor decreases were observed in 2019/20 relative to 2018/19.

Plant height at maturity per DI and ISFM treatment are presented in Appendices, Supplementary Table S8. Irrigating 100% ETc at L1, L2, L3, M and C gave the largest average plant heights at maturity of 93, 92, 89, 91 and 87 cm, respectively. The lowest plant height recorded at maturity was 81 cm, which was observed at 50% ETc under C. Plant height as a yield attribute might be a good proxy to assess the total biomass needed for livestock fodder. Fig. 1 shows a good correlation between biomass and plant height, with biomass of wheat increasing linearly with plant height and 57% of the variation in biomass being explained by plant height.

Being an indicator of grain quality, thousand-grain weight (TGW) was determined as presented in Supplementary Table S8 per DI and ISFM treatment. In line with the other findings, TGW was significantly affected ($p < 0.05$) by DI and ISFM. The TGW values were higher at L1, L2, L3 and M (in that order) than at C, irrespective of moisture deficits. However, the effects of DI and ISFM were less pronounced as compared to those of crop yield and biomass. For example, a 50% moisture deficit, reduced TGW by 4–10% under L1 to L3, 2–2.2% under M, and 2.3–4.7% under C in comparison to full irrigation. A highly significant linear relationship was observed between yield and TGW (Fig. 2), with TGW explaining 76% of the variation in yield.

3.3. Grain yield per applied irrigation water amount and water productivity

Table 2 shows that yield of wheat in 2018 and 2019 calculated per total irrigated water amount (AIW) was increased with increasing water deficit strategies. For example for L1, the average grain yield (over the two seasons) was 5.5 t ha^{-1} under 100% ETc and 5.0 t ha^{-1} under 50% ETc. Since under the latter regime, 46% less water is used and thus 1.85 times as much land can be irrigated with the same amount of water (Supplementary Table S3), the overall yield becomes 10.2 ton per 1.85 ha.

Also, 50% ETc DI applied under C yielded on average 5.0 t per 1.85 ha with an irrigation amount equal to AIW, which is only slightly less than the overall yield at 100% ETc with L1 (5.5 t) and equal to that at 100% ETc under L3. Similarly, on average, 50% ETc DI at M produced 8.7 t per 1.85 ha, which was always much higher than the overall yield at 100% ETc at all lime doses (5.0–5.5 t). Compared with 100% ETc full irrigation, the overall yield per unit of AIW increases with increasing water stress regardless of the ISFM treatments.

In all ISFM scenarios, the yield increase per unit of water consumed was higher in the 50%, 60% and 80% ETc irrigation scenarios (in that

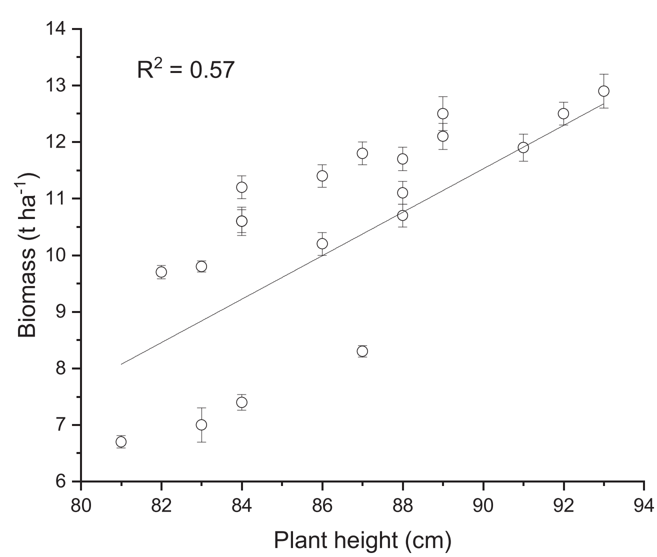

Fig. 1. Relationship between biomass yield and plant height of wheat from two irrigated season data (2018 and 219), n = 20.

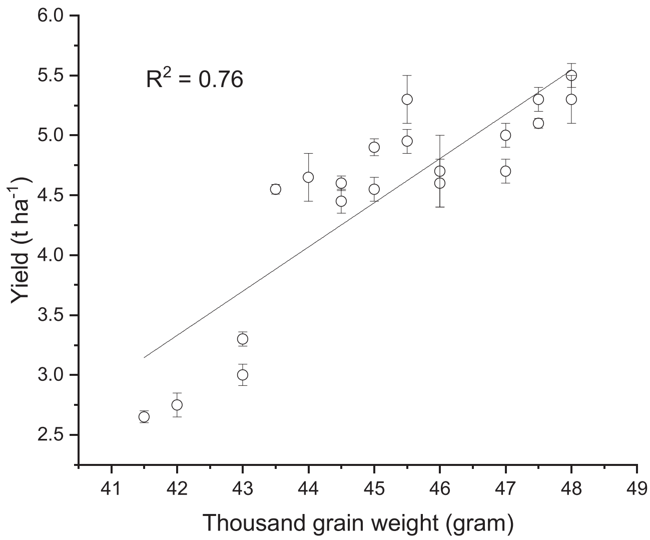

Fig. 2. The relationships between wheat grain yield and thousand−grain weight for 2018 and 2019 irrigated seasons, n = 20.

order). But, at 100% ETc irrigation scenarios, there is no yield increase, because there is no saved water to irrigate extra land which increases yield. In each irrigation scenario, the yield increase per unit of AIW appears to be higher at M, however, this is due to the lower yield reduction at M compared to lime and manure (L1–L3) received plots (see Table 3). Indirectly, DI enhanced yield per unit of water applied regardless of which ISFM was used, and as the degree of water stress increased, the yield improvement per unit of water used likewise increased.

In a similar fashion, DI and ISFM treatments significantly influenced water productivity (WP) during the study period as shown in Fig. 3. Water productivity was always highest under the lowest irrigation water regimes or the highest water saved and decreased linearly with more water being applied. This was the case for all ISFM treatments.

Notably is that the decrease in WP from least to most irrigation water was similar for all lime and manure treatments (L1-L3, M), which showed a similar slope of the regression line. These treatments made WP increase up to 67–68% when the amount of irrigation water almost halved (50% ETc) in comparison with full irrigation. Notably is that WP values of L3 and M were most comparable. The C treatment however showed a relatively lower response to variation in irrigation strategy, with an increment of 52% with about half the amount of irrigation water. But even more important than the water saved and being less consumed under the DI regimes was the increase in yield resulting from the ISFM treatments. In comparison with C, WP now increased by 15–68% under L1-L3 depending on DI. At M, the increment still ranged between 20% and 75% across DI treatments. In all DI treatments (100% ETc, 80% ETc, 60% ETc and 50% ETc), the highest WP was found at L1 compared with the other ISFM treatments.

3.4. *Effect of DI and ISFM on soil moisture availability and plant gowth stages*

Fig. 4 shows the soil water content (SWC) of the soil profile (0–60 cm) measured one day and two days after irrigation sessions from all DI and ISFM treatments under the irrigated wheat growing seasons (2018/19–2019/20). Under 100% ETc in all ISFM treatments, the crop growth stages experiences no water stress except at C, where the crop experienced water sress at maturity followed by ripening stages. Perhaps, the soil fertility stress due to soil acidity could be a possible reason for the lower soil moisture availability for crops at C. But, the water stress occurred at maturity and ripening stages may not significantly affect the wheat yield. Regardless of the ISFM, at 80% ETc the crop experienced a modest moisture stress that leads to stomata closure at flowering, maturity and ripening stages.

In all ISFM treatments at 60% ETc, the crop was exposed to water stress the whole growth stage but was highly stressed at the maturity and ripening stages, while at C, the stress occurred starting from around early flowering, development, maturity and ripening stages. This implies that the soil fertility stress exacerbated the water stress level at C. At 50% ETc, the level of water stress was higher at C in all growth stages but at L1, L2, L3 and M the flowering, maturity and ripening stages were considerably stressed. The trends of SWC throughout the cropping periods were consistent, indicating that the watering was applied with a predetermined schedule and amount.

3.5. *Gross profit*

Under all treatments, the input costs were in the order of L1 > L2 > L3 > M and C (Table 3). At full irrigation (100% ETc), the order of gross profit per ha was L1 > M > L2 > L3 and C, whereas, at 80% and 60% ETc, the order was M > L1 > L2 > L3 and C. Reducing the irrigation water amount under M was always more profitable per ha,

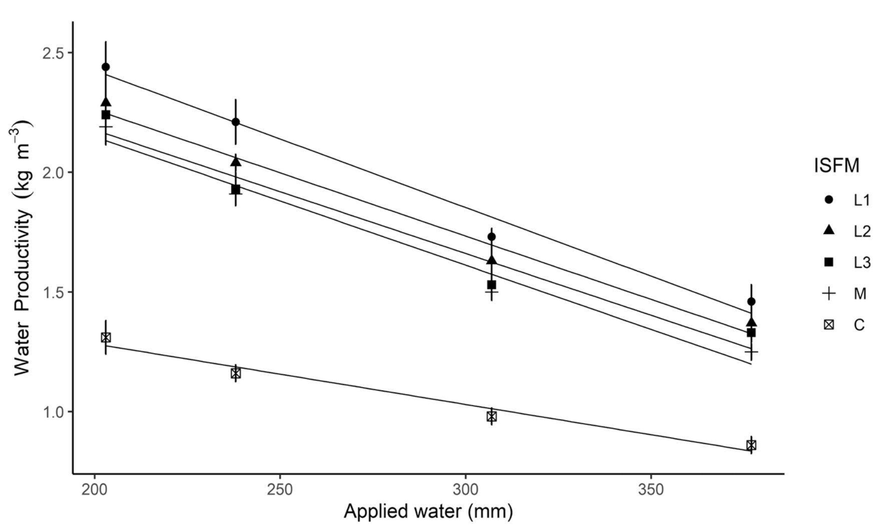

Fig. 3. Average seasonal applied irrigation water of the crop water requirement calculated for the local wheat variety in the study area, see Supplementary Table S3) under varied integrated soil fertility management (ISFM) and mean water productivity per applied irrigation water (WP_{AIW}) for data of 2018 and 2019. L1, L2, L3, M and C as in Supplementary Table S2. N = 6. Vertical bars indicate standard deviation.

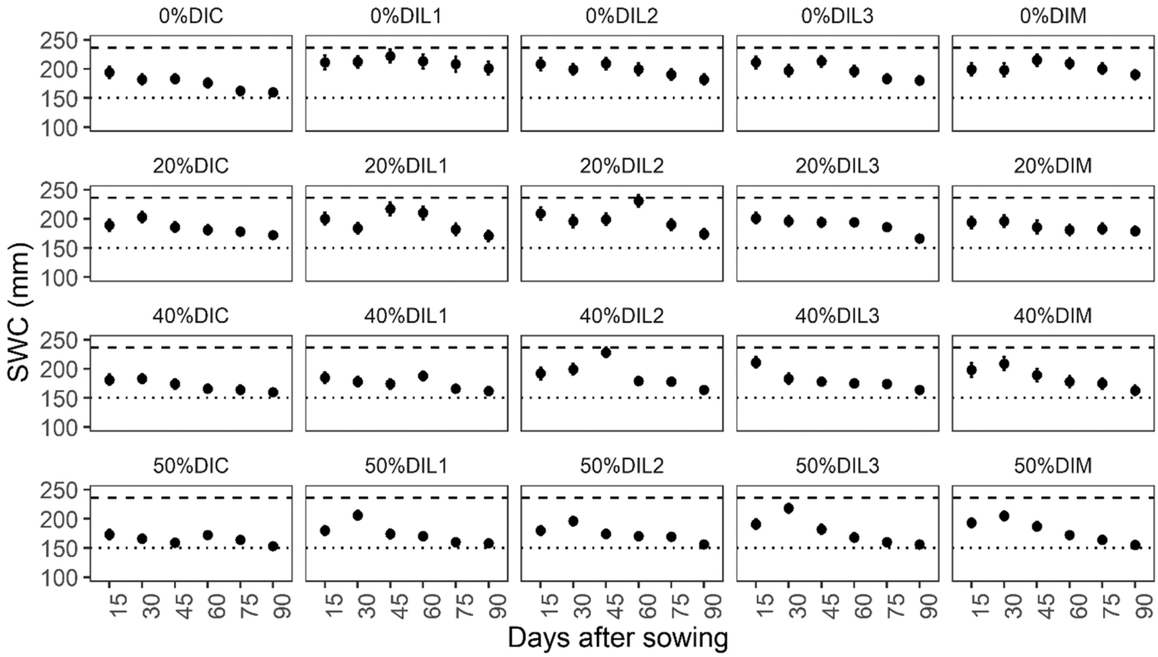

Fig. 4. SWC under ISFM and DI (• are measured SWC, ... measured SWC at permanent wilting point, — measured SWC at field capacity) for 2018/19 at 60 cm soil depth. 0%DI indicates full watering (applying 100% of seasonal ETc); 20%DI indicates irrigating 80% of seasonal ETc; 40%DI indicates watering 60% of seasonal ETc; 50%DI means watering 50% of seasonal ETc. For L1, L2, L3, M and C, see Supplementary Table S2. Vertical bars indicate standard deviations (±). The graphs are too small, then difficult to see the differences in FC and PWP between treatments throughout the growth stages.

even without adding lime (L1-L3) than full irrigation under C. Manuring only (M) at 50% ETc was more profitable per ha than adding lime in addition to manure (L1-L3) under 60% ETc. At 80% and 100% ETc, adding lime was more profitable per ha (except for L3 under 80% ETc) compared with M at 50% ETc.

Calculating the gross profit per amount of water and thus using the water that could be 'saved' by not fully irrigating individual fields, sheds another light on the findings. The order of gross profit per AIW at full irrigation (100% ETc) and 80% ETc, was L1 > M > L2 > L3 and C, whereas, at 60% ETc, the order was M > L1 > L2 > L3 and C. Yet, at 50% ETc the order of gross profit per AIW was L1 > M > L3 > L2 and C. Amazingly, wheat production profitability increases now tremendously with increasing deficit irrigation levels. The highest profitability per AIW was found under L1 with 50% ETc. This combination almost doubled the profitability in comparison with full irrigation (100% ETc) under the ISFM treatments (L2, L3, M and C). All 50% ETc DI treatments, even the control without any extra manure or lime, were more profitable than all 100% ETc treatments.

4. Discussion

4.1. Yield per unit of land and biomass production

The effect of DI combined with integrated soil fertility management (ISFM) on water productivity (WP) and wheat production was studied over two irrigated seasons in 2018 and 2019. Yields in the 2019 wheat season were slightly higher than those in the previous season (Table 1), which was most likely due to improved soil conditions because of the residual effect of previous liming and manuring, as well as the return of crop residue and straw which may increase soil organic matter. Weather conditions in both years were very similar (Supplementary Table S1).

As expected, wheat production per ha increased with increasing irrigation water amount under all ISFM treatments (Table 1). The lower grain yield and biomass found at DI under all ISFM treatments compared with full irrigation could be due to moisture stress which may reduce photosynthesis and other cellular functions, and damage the reaction center of the photosystem, ultimately reducing grain yield and biomass (Dhiman et al., 2019; Ferreira et al., 2019; Greaves and Wang, 2017; Guo et al., 2013; Gurmessa, 2020; Junior et al., 2020). A decreased wheat grain yield and biomass with increasing moisture deficit was also reported by Ding et al. (2021), Jemal et al. (2019), Meskelu et al. (2017) and Tavakoli and Moghadam (2016) from DI field trials.

Irrespective of the DI strategy, the grain yield and biomass were higher in the ISFM treatments L1, L2, L3 and M compared with C. The improvement in soil quality of the acidic Nitisol, such as soil structure, bulk density, porosity, air capacity and water holding capacity mainly water content at FC, as demonstrated by Asmamaw et al. (2022) in the same field trial, could be one reason. A better physical soil environment can promote root growth and reduce non-productive water flow, most like soil evaporation, rather than deep percolation given that irrigation doses were as such that they replenish soil to field capacity. Also, the increase in pH and soil organic matter by liming and adding manure (Asmamaw et al., 2022) could have made adequate basic nutrients more available for uptake by plant roots, with L1 showing the highest impact on yield and biomass in comparison with L2, L3, M and C (in that order). Liming reduces aluminum and hydrogen toxicity, and thus promotes normal plant growth and enhances the plant's nutrient and water uptake leading to increased grain yield and biomass (Auler et al., 2017; Demil et al., 2020; Dhiman et al., 2019; Ferreira et al., 2019; Gurmessa, 2020; Junior et al., 2020). This is supported by the findings of Marschner (2011) who reported that the application of lime reduced soil acidity which enhanced better crop growth that can provide additional organic matter through residue returns and free calcium carbonates which help increase soil pH, improve the solubility and availability of important nutrients to plants, and improve the water-holding capacity and uptake of nutrients.

Interesting is that DI was most successful, i.e. showing the lowest yield penalty, under M. It was having the largest negative effect under C. Vice versa, the highest response to ISFM was found under the most deficit irrigation strategies, and the lowest at full irrigation. This could indicate that liming will primarily increase the availability of nutrients, while manuring creates a better physical soil environment. Since nutrients can only move to roots through continuous water films within the soil, reduced water contents and lack of water continuity in soils associated with the increased level of DI will reduce nutrient uptake rates (Auler et al., 2017; Gurmessa, 2020; Junior et al., 2020; Shaxson and Barber, 2003). Under manuring alone, this effect seems less important, and the effect of manuring is probably limited mostly to a higher physical resilience to water stress, resulting from higher organic matter content and microbial activities that can promote soil aggregation (Ferreira et al., 2019; Lal & Shukla, 2004). The C treatment without having manure being added therefore shows a much larger yield penalty with increasing water stress than the M treatment. In a study on wheat production under different DI and fertility strategies on a deep clay silty soil in Northwest Iran, Tavakoli and Moghadam (2016) showed that the application of 67% ETc combined with 90 kg N ha^{-1} reduced grain production by 20% compared to 100% ETc. But, at full irrigation, a 68% yield improvement was found due to 90 kg N application compared with no fertilizer used. They concluded that enhancing soil fertility combined with DI might result in a significant and consistent improvement in wheat yield in semi-arid regions.

For farmers, improved soil and irrigation water management approaches that could improve grain yield are vital (Asmamaw et al., 2021a, 2021b). Also, producing more biomass as such is crucial as livestock ranching is the secondary agricultural activity that needs the straw for animal fodder (Amede et al., 2021; Agegnehu et al., 2017; Desalegn et al., 2017). The lowest grain yield found from C coincides with the national (2.5 t ha^{-1}) and global (2.9 t ha^{-1}) average wheat yield (CSA, 2021; Minot et al., 2015). Adding relatively low amounts of water (as under DI) in combination with improving soil health can thus more than double the biomass and yield of wheat, even in a dry season. The lowest yield found in C at 50% ETc could be attributed to the aluminum toxicity which restricts root growth that hampers water uptake of plants and the nutrient's unavailability to plants due to soil acidity. This means the plants could not use the applied DI and nutrients. The lowest yield found in C at 50% ETc could also be caused by a moisture shortage. But, with the same amount of DI used at L1, L2, L3 and M, higher yields were discovered. This means plants can access the available water. This depends on root depth. Adding lime increased the availability of P which might have stimulated root growth (and thus increasing root depth). As a result, not only the accessibility to water increases but also that to nutrients.

4.2. Grain yield per applied irrigation water amount and water productivity

Though there was a small yield penalty per ha under DI, it increased the overall wheat production per unit of water application in all ISFM practices when compared to full irrigation (Table 2). The overall yield increase per unit of AIW under all ISFM suggested us the possibility of expanding the currently irrigated area by irrigating extra land with the saved water. When 80% ETc, 60% ETc and 50% ETc irrigation strategies are used, 23%, 58% and 85% irrigation water can be saved compared to full irrigation with the same amount of water used. For instance, at all ISFM practices, 50% ETc application almost doubled the overall yield by irrigating about 85% more irrigable land using the saved water. This way, water scarcity could be reduced in areas where moisture is the limiting factor for crop production. Thus, in the Koga irrigation scheme, these irrigation scenarios could increase the irrigable area as displayed in Fig. 5, where command areas were delineated by considering a slope of less than 6%, land leveling and farmers' settlement. Also, the yield increase for each scenario under each ISFM treatment is shown in Table 2. This means that those farmers that are currently not irrigating their land due to water shortage, though initially considered in the project, could now benefit from it. Yet, to be more beneficial from DI, amending the soil with lime and manure seems an interesting option as our findings suggest that the small yield penalty due to DI could be compensated by soil fertility management. In line with this study, Ding et al. (2021) concluded that applying compost could be used to mitigate the wheat yield penalty effect of DI in Egypt under a silt-clay-dominated Aridisol.

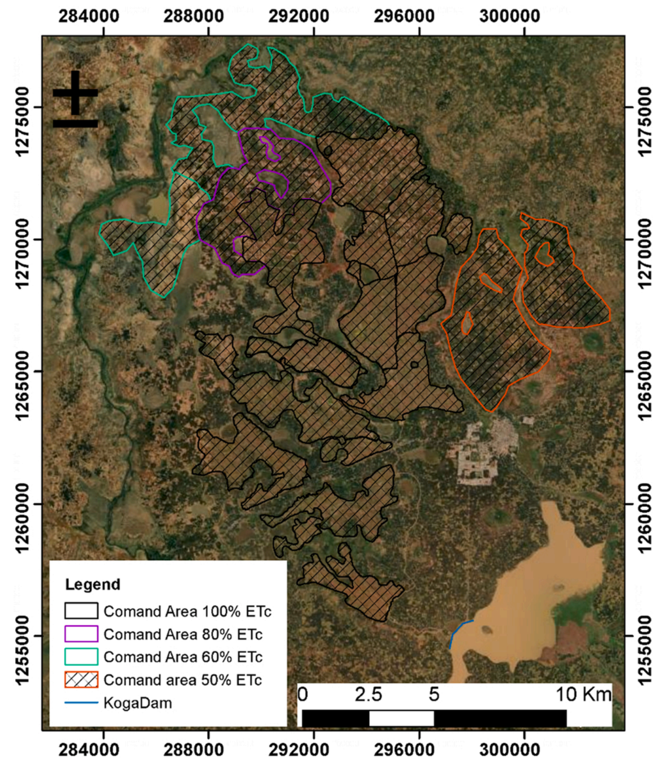

Fig. 5. Map showing the currently irrigated area by 100% ETc which is delineated by black color, the potentially irrigated area using 80% ETc scenario that includes the currently irrigated area plus the area delineated by violet color, the potentially irrigated area using 60% ETc and 80% ETc scenarios plus currently irrigated area using 100% ETc, and the potentially irrigated area using the 50% ETc scenario which includes the currently irrigated area plus a potentially irrigated area with 80% ETc and 60% ETc scenarios.

Water productivity (WP) can be improved by applying DI (Admasu et al., 2019; Ali et al., 2019; Flörke et al., 2018; Gahnnem et al., 2021; Qin et al., 2022; Singh et al., 2021; Tari, 2016; Yu et al., 2020) and ISFM practices, as the first reduces the amount of water consumed, while the latter increases crop yield (Ding et al., 2021). Considering only the liming and manuring effects in all irrigation scenarios (100% ETc, 80% ETc, 60% ETc and 50% ETc), the increment in WP followed the order of L1 > L2 > L3 > M > and C (Fig. 3). Yet, regardless of the ISFM, WP increased with increasing moisture deficit. The highest WP we found from 40% and 50% DI can be attributed to the wise use of irrigation water and reduced non-productive water flux (mostly evaporation), while at 100% ETc, part of the irrigation water may not be efficiently used by the crop but rather be lost in the form of evaporation.

As the irrigation water applied at full irrigation was done to replenish the depleted water from the root zone by the researcher, there was no excess water that could be deep percolated. The capillary rise was assumed to have a negligible contribution to the root zone, as the water table was found below 5 m from the surface and capillary rise was estimated at 1.1 m only. In all ISFM treatments, the stored soil moisture content decreased with increasing the moisture deficit (Supplementary Table S9). In comparison to C, the lime treatments (L1-L3) increased soil moisture content up to 14–39% depending on the DI levels. At M, the increment ranged between 7% and 10% compared with C. In comparison with full irrigation, the soil moisture content stored at lime treatments (L1-L3) reduced between 16% and 24% at about half of the irrigation water used, but at M and C, it decreased by 16% and 13%, respectively. Also, lime and manure were clearly shown to enhance WP.

Hence, investing in lime and manure could also save more water that could be used to irrigate extra land.

When compared with the control (no liming and manuring), WP at 50% ETc is 67–86% higher under lime and manure treated fields (L1 to M) (Fig. 3). Our results comply with that of a recent review (Asmamaw et al., 2021a, 2021b) that reported a 27% maize yield reduction but a 109% WP increase when saving 65% water. In a DI field trial carried out in Ethiopia on clay soil, Jemal et al. (2019), Mahamed et al. (2011) and Meskelu et al. (2017) reported improved wheat WP under DI compared with full irrigation.

4.3. Thousand grain weight under DI and ISFM

The value of TGW, a grain quality indicator, is very essential to determine the seed rate. A high TGW is mostly associated with large grain size, hence farmers need more seeds, while they need less for low TGW. Our findings suggest that wheat grain quality is moderate to low in its sensitivity to water and soil fertility stress. The grain yield of wheat increases linearly with increasing TGW (Fig. 2). This means that the heavier grain weight and highest grain yield observed at lower moisture deficits combined with the highest lime doses are likely due to adequate nutrient availability and more translocation of food processed in photosynthesis due to adequate water in the root zone compared to other treatments.

Compared with C, the combined application of lime, manure and inorganic fertilizer improved TGW irrespective of DI applications. Liming improves the ability of the plant to absorb nutrients by eliminating Al toxicity and by increasing the vegetative growth of wheat, which resulted in increased TGW. Regardless of liming and manuring, the values of TGW decrease with an increasing water deficit in all treatments. This implies that photosynthesis, respiration and other cellular functions of plants are more affected under 60% or 50% ETc compared with 100% ETc and 80% ETc. In a previous study, Meskelu et al. (2017) reported the highest TGW at 100% and 85% ETc compared with 50%, 40% ETc and 30% ETc under clay soil in Ethiopia. Mahamed et al. (2011) reported significantly decreased wheat TGW with increasing soil moisture depletion levels due to DI application compared with non-water-stressed plots in semi-arid Ethiopia under Haplic Andosol. Also, Tari (2016) found a 37% reduced TGW value of wheat over an optimally irrigated clay-dominated soil in Turkey. This implies that to some extent imposing water stress could contribute to the reduction of TGW as the amount of available water may not be sufficient for producing better grain. The decrease in irrigation water level decreases the plant height in all ISFM (Supplementary Table S8). This showed that plant height is mainly affected by moisture stress due to the reduction in photosynthesis of the plant.

4.4. Gross profit

Irrespective of the ISFM, DI improved the profitability of wheat production in comparison with (100% ETc) full irrigation. This means profitability increases with increasing moisture deficit. Among the tested ISFM treatments, L1 requires the highest investment but it is the most profitable strategy compared with L2, L3, M and C (Table 3) at 100% ETc, 80% ETc and 50% ETc. Under 40% DI, manuring is the most profitable followed by L1, L2, L3 and C, respectively. This means that the combined use of manure and lime was found to be more important to increase gross profit rather than the use of inorganic fertilizer alone, which produced a low yield. When DI alone is considered, a 50% moisture deficit is more profitable followed by a 40% and 20% deficit, respectively. As such, with a 50% ETc in all ISFM treatments, grain yield is close to double, resulting in higher profitability. This infers that by DI, farmers can irrigate more land with the saved water which improved their gross profit compared with the full irrigation strategy as described earlier. This also can be taken as a climate change resilient strategy particularly, in the time of prolonged dry seasons.

In general, the use of DI and ISFM improves profitability. In addition, when the moisture deficit increase, profitability raised linearly. Thus, farmers could choose one of the ISFM and DI strategies based on their lime purchasing power, water and land availability.

5. Conclusion and recommendations

The effect of integrated soil fertility management (ISFM) and deficit irrigation (DI) on wheat production and water productivity (WP) was studied. Applying full-dose lime combined with manure substantially enhanced wheat grain yield, biomass and WP compared with 80% of the lime requirement (LR) and 60% of LR combined with manure at 100%, 80%, 60% and 50% ETc scenarios. Manure application also considerably improved wheat grain yield, biomass and WP under all irrigation water scenarios. The highest WP was found at 100% of lime requirement (L1), 80% of lime requirement (L2), 60% of lime requirement (L3) and 3 t ha^{-1} manure (M) respectively, possibly because of increasing organic matter and improved basic nutrients available for plants at all irrigation water levels. We note that liming and manuring could be used to mitigate the yield penalty effect of DI, while it further increases WP in the study area. This could help with the decision of choosing soil and water management strategies that could be used to reduce yield loss due to soil acidity-induced soil fertility stress and water stress.

The overall yield increase per unit of applied irrigation water for each scenario under all ISFM suggested the possibility of expanding the existing irrigated area by irrigating additional land with the saved water. This means that farmers who are currently unable to irrigate their land owing to a lack of water, though initially were considered in the project, could now benefit from it.

The use of L1 under full irrigation 100% ETc, 80% ETc and 50% ETc is the most profitable strategy, whereas manuring is the most lucrative strategy under 60% ETc. When we considered irrigation water management alone, a 50% DI is more profitable than 60%, 80% and 100% ETc. Thus, farmers could choose one of the tested ISFM strategies based on their lime purchasing power, water availability and extra land available for irrigation. From an irrigation water management viewpoint, wheat could be irrigated at 60% ETc to increase WP with less grain yield reduction at L1, L2, L3, M and C. To save more water to irrigate extra irrigable lands currently not irrigated in the Koga irrigation area, farmers should invest more in DI integrated with liming and manuring.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.108077.

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