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TOPICAL REVIEW

Deficit irrigation as a sustainable option for improving water productivity in Sub-Saharan Africa: the case of Ethiopia. A critical review

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Abstract

Improving irrigation water management and enhancing water productivity (WP) is required to address future water scarcity in the sub-Saharan region. Maximizing WP by exposing the crop to a certain level of water stress using deficit irrigation (DI) is considered a promising strategy. To adopt DI strategies, a shred of comprehensive evidence concerning DI for different crops is required. This review aims to provide adequate information about the effect of DI on WP. The result showed that DI considerably increased WP compared to full irrigation. Despite higher WP, the reduced yield was obtained in some of the studied DI practices compared to full irrigation. It was also found that yield reduction may be low compared to the benefits gained by diverting the saved water to irrigate extra arable land. Maize revealed the highest (2.7 kg m^{-3}) and lowest (0.5 kg m^{-3}) WP when irrigated at only the initial stage compared with being fully irrigated in all growth stages. Also, onion showed a decreasing WP with increased irrigation water from 60% crop water requirement (ETc) (1.8 kg m^{-3}) to 100% ETc (1.3 kg m^{-3}). Increasing water deficit from 100 to 30% ETc led to an increase of wheat WP by 72%. For tomato, the highest WP (7.0 kg m^{-3}) was found at 70% ETc followed by 50% ETc (7.0 kg m^{-3}) and 85% ETc (6.9 kg m^{-3}), while 100% ETc showed the least WP (6.8 kg m^{-3}). Teff showed the lowest WP (1.7 kg m^{-3}) under optimal irrigation, while it was highest (3.0 kg m^{-3}) under 75% ETc throughout the growing season. The regression analysis for WP increment and yield reduction versus saved water showed higher values, indicating that DI could be an option for WP increment and increasing overall yield by expanding irrigated area and applying the saved water in water-scarce regions.

1. Introduction

Food production requires to increase to feed the growing world population (Bouman 2007). This increase needs to be accomplished under a changing climate, so water shortages might increasingly materialize (Scheierling and Treguer 2016). With the growing water shortage in developing countries, enhancing agricultural water management strategies is of paramount importance to reduce food insecurity (Giordano *et al* 2016). Increasing water productivity (WP) is mainly suitable where water is limited compared with other resources involved in crop production (Molden *et al* 2010). In this study, water productivity (WP) is defined as the ratio of harvestable wheat grain yield (Y, kg) divided by the accumulated amount of water consumed by evapotranspiration during the growing season (ET, m^3). Today, many countries are experiencing a scarcity of blue and green water resources (Rockström *et al* 2007, Pereira *et al* 2012). The problem is more evident in tropical regions (Fereres and Soriano 2007, Ambachew *et al* 2014). The emerging water demand and unproductive uses are conceivable to widen the gap between water supply and demand (FAO 2011). Hence, more attention should be given to the long-term sustainability of agricultural production by improving WP. If not, it is hardly possible to address the food demands of the world population that is expected to surpass 7 billion in the 2020 s (FAO 2011).

Besides, to sufficiently feed the 9.3 billion people by 2050, consumptive water use needs to raise from 7,000 km^3 $year^{-1}$ to over 12,500 km^3 $year^{-1}$ (Falkenmark and Rockström 2004). Plants need plenty of water to produce food; when rain cannot supply it, irrigation can make up the deficit. However, available freshwater resources are limited so that higher productivity of irrigation strategies is required. According to Rockström *et al* (2007), an increase of 30 and 60% in WP will be required to encounter the demands for food security in the future from rain-fed and irrigated agriculture, respectively. Increasing irrigation WP improves food production and offers scope for crop diversification (Mengistie and Kidane 2016).

Moisture stress due to inadequate water supply in the sub-Saharan African (SSA) region where rain-fed agriculture is the backbone of the national economies is growing (Rockström *et al* 2010, Linker *et al* 2016). Introducing irrigation technologies that suit local situations can contribute to reducing this problem (Fereres and Soriano 2007, Geerts and Raes 2009).

Ethiopia is gifted with ample water resources and is considered the 'water tower' of North-East Africa. Twelve river basins offer a projected annual runoff of 122 billion m^3 (Awulachew *et al* 2010, Yihun 2015). While the country has enormous water resource potentials, irrigation development has a slight contribution to national development. Nevertheless, due to lack of *in situ* green and blue water management (Asmamaw 2015), absence of water storage infrastructure, deep, narrow, and rapid falls of the rivers, and large spatial variations in water resource distribution (Awulachew *et al* 2007), there is water scarcity for farmer's who fail to produce more than one crop per year, with frequent crop failures due to extended dry spells and frequent droughts (Awulachew *et al* 2010).

Approaches dealing with improved WP such as water-saving irrigation technologies (Ali and Talukder 2007, Geerts *et al* 2010) and better soil management practices (Prosdocimi *et al* 2016) are considered important. Among others, deficit irrigation (DI) is a promising option for farmers, who endeavor to improve the output of their limited land and water resources in areas where the available water supply is too low to provide an acceptable yield (Geerts and Raes 2009). In this study, DI is defined as an irrigation strategy whereby a crop is watered (full ETc, mm/day) in drought-sensitive growth stages, while watering is limited (below ETc) in less drought-sensitive periods or during the whole growing period (Geerts *et al* 2010). ETc is crop evapotranspiration representing crop water requirement (ETo^*Kc). DI is comparatively inexpensive and easy to apply (Geerts and Raes 2009) and stabilizes crop yield with limited water (Heng *et al* 2009). It has been widely studied as an appreciated and viable production approach for a wide range of crops in water-limited regions (Rosin *et al* 2017).

As long as the soil fertility is favorable and the crops are applicable for the DI strategy, DI enhances WP in comparison with full irrigation (Geerts and Raes 2009, Pereira *et al* 2012). Hence, DI can contribute to (i) lessening overall water demand; (ii) reduce the decline of land productivity allied with soil erosion, waterlogging, and salinization; (iii) decrease operation and maintenance costs related to desilting and water outtake including the costs of pumping, delivering water or water fees; (iv) increase irrigated areas with the same amount of irrigation water; and (v) improve agricultural output, food security, and profitability (Geerts and Raes 2009). Also, Molden *et al* (2010) confirmed that improving agricultural WP using DI is expected to (i) meet rising demands for food from a wealthier, and rapidly growing urbanized population in light of limited water; (ii) to respond to pressures to re-allocate water from agriculture to cities and ensure that water is accessible for ecological uses; and (iii) to contribute to poverty reduction and economic growth.

In developing countries, many of the irrigation strategies are traditional and are based on farmer's local knowledge (Tsegay 2012, Beyene *et al* 2018). This means that when water is available, farmers irrigate their fields without any gauging mechanism. Hence, crops are watered more than they require (Hagos *et al* 2009, Beyene *et al* 2018). Most of the farmers irrigate their fields by flooding though flood irrigation is known to be a traditional irrigation method due to its inefficient water use (Beyene *et al* 2018). Farmers do not get enough expert advice regarding when, how, and how much water to irrigate (Mengistu 2009). Farmers diverted water from rivers and springs using unlined canals, and the water use association committee allocated water on a rotation base for irrigation purposes (Derib *et al* 2011). Yet, the schedule does not consider the type of crops irrigated and the size of the fields, but it only considers the number of water users (Beyene *et al* 2018). The application of the right amount of water to the crop at the right time is a big concern in various irrigation schemes, which need local solutions (Hagos *et al* 2009). Awulachew *et al* (2010) argued that in Ethiopia, many irrigation schemes do not perform according to the design expectations, most probably due to over-irrigation practices, which means WP is lower than the optimum. Meanwhile, not enough water resources are available to irrigate all arable land.

Increasing agricultural WP enabling households to generate more income, increasing their resilience as well as changing their livelihoods stands out as the most pressing agenda now and for the coming decades in Ethiopia (Mengistie and Kidane 2016). Hence, improving agricultural water management is essential and could be of social, cultural, and economic importance to the beneficiaries (Molden *et al* 2010).

Although irrigation is an old age practice in Ethiopia, very low WP has been documented (Hordofa 2006, Erkossa *et al* 2011a). Hence, to focus on efforts that can augment WP in irrigated agriculture, inclusive evidence and adequate knowledge concerning DI effect on WP and crop yield are desirable. Though there are many field trials on DI, there is a scarcity of comprehensive review studies about DI effects on WP and yield that can be used as a reference for scholars and practitioners in both Ethiopia and Sub-Saharan countries. This review paper, therefore, aims to bridge this knowledge gap and provide adequate information about the impact of DI strategies on maize, onion, wheat, tomato, and teff WP and crop yields, which is useful for growers, researchers, planners, and decision-makers.

2. Methodology

In Ethiopia, cereal crops are mostly grown during the main rainy season (June to September). However, maize (*Zea mays* L.), onion *(Allium cepal.)*, wheat (*Triticum aestivum* L.), tomato (*Solanum lycopersicon* L.), and teff *(Eragrostic Tef)* are grown in the dry season as well using irrigation. During the wet season, some farmers also apply supplemental irrigation.

Ninety studies were considered for this study. Once the data were collected, we conducted a systematic screening to keep those studies that contented the criteria. For a study to have met the chosen criteria, it must: (i) have an experimental set-up within Ethiopia; (ii) have a control, treated the same way apart from the irrigation water being studied; (iii) have randomized and well-designed experiments with three replicates; (iv) have been published in a peer-reviewed journal; (v) be deficit irrigation-based. Studies that did not meet the aforementioned criteria were excluded.

When reviewing the effect of DI on yield and WP of irrigated crops, it was noticed that for the same amount of irrigation water applied to the same crop, significantly different yield and WP values were reported. This is probably due to differences in soil fertility levels, salinity, field management practices, climate variability, drainage, pests, disease, soil water evaporation, and other factors. The amount of irrigation water was expressed in terms of ETc (calculated based on the FAO crop water requirements approach (Allen *et al* 1998). All the field experiments base papers cited in this manuscript calculated reference evapotranspiration (ETo) using ETo calculator developed by FAO using site-specific daily weather data as described by the Penman-Monteith (Allen *et al* 1998). For all studied crops, the kc values are available in FAO-published papers. Then, ETc was estimated as ETo * kc for each crop. To exclude the effect of factors different from the amount of water applied when analyzing the data, the WP values were normalized by expressing them relatively to the WP values obtained from 100% ETc in a particular study. Likewise, the yield was expressed relative to 'potential' yield, i.e., at 100% ETc. In all experiments, 100% ETc was thus, considered as a control. To illustrate the effect of DI on yield reduction and WP increment versus the percentage of water saved, correlations were made using linear regression models. The main reasons why we have calculated the water productivity increment and yield reduction due to DI application was to have a clear understanding of DI strategy and to explore its potential and to reach practical suggestions for farmers. Prior to this, a test of data normality was undertaken. Statistical analysis and graphics were done in the R environment (version 3.4.2.).

Water productivity increment (WP) was obtained by the WP found at DI treated plots minus WP obtained at full irrigation multiplied by 100%. The yield reduction was obtained by yield recorded at DI treated plots minus yield obtained at full irrigation multiplied by 100%. The calculation procedure works for all yields obtained in all DI treated plots against full irrigated crops. We further calculated the increase in overall yield when more land would be deficit irrigated with the water saved per hectare, i.e., using the same amount of water as under full irrigation. Calculations were based on the yield and DI water amounts in the percentage of ETc provided in the papers. First, an irrigation area expansion factor which is the applied amount of water under full irrigation over that under DI (in terms of % ETc) was calculated (100% ETc/DI% ETc). This factor was then multiplied with the yield obtained per hectare under the respective DI strategy giving the overall yield, i.e., the yield when using the same amount of water as under 100% ETc but now spread over more land. This overall yield was then expressed relative to the yield under 100% ETc allowing to determine the percentage of overall yield increase. For example, consider that crop yield is 4.5 t ha^{-1} under 100% ETc (full irrigation) and 4.0 t ha^{-1} under 70% ETc (DI). Under DI, 30% of water is saved and the irrigated area can be expanded with a factor of 1.43 (i.e. 100% ETc/70% ETc). Under DI, when now using the saved water to expand the deficit-irrigated area, the overall yield becomes 5.7 t (per 1.43 ha) (i.e. 4.0 t ha^{-1} multiplied by 1.43). Considering that there is crop failure when fields are not irrigated (which is most probable in the dry season), it means that under the full-irrigation regime overall yield remains 4.5 t ha^{-1}. The yield gain by applying 70% ETc but with the same amount of water as under 100% ETc is thus 27% (as yield has increased with a factor of $1.27 = 5.7$ t/4.5 t).

Summary tables that give the percentage of water saved, yield, yield reduction, overall yield increase per hectare with the saved water, WP, and WP increment for maize, onion, wheat, tomato, and teff are presented in the annex section as supplementary material.

3. Irrigation water management

In most of the cited papers included in this report, researchers irrigated the field trials using furrow irrigation practice. They applied DI either stage-wise or throughout the whole crop growth stage. When stage-wise DI is applied, researchers withhold water at one or more of the main crop growing stages (i.e. emergence, vegetative, flowering, and maturity) and fully irrigated (100% ETc) at the remaining stages. On the other hand, researchers implemented the DI throughout the whole crop growth stages by reducing the net irrigation requirement (100% ETc) by 10%, 15%, 20%, 25%, 30%, 35%, 40%, and 50% of the studied crops and applied 90%, 85%, 80%, 75%, 70%, 65%, 60% and 50% ETc, respectively.

A constant discharge from nighttime reservoirs and variable discharge from the rivers was diverted into the experimental fields. This discharge was allowed to flow into a plot at a time. With the help of a calculator and a stopwatch, the flow into each plot and the time required to apply the desired depth of water were instantly calculated as soon as water was guided into the plot. Water was then discharged into the plot and each furrow for the calculated time. 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 was estimated as:

$$Q = KH_a^n \tag{1}$$

where Q is the free flow rate (m^3 s^{-1}), K is the flume discharge constant, H_a is the depth at the point of measurement (mm), and n is the discharge exponent.

The DI application was managed by reducing the time required to irrigate the predetermined areas using calibrated Parshall flume. The water application was accomplished by decreasing the time allocated to apply the depth of the calculated water. The time required to irrigate the plots with the predetermined amount of water was estimated as:

$$\text{The time required (minutes)} = \frac{10 \times a \times d}{q \times 60} \tag{2}$$

Where ‘a’ is the area of the plot to be irrigated (m^2), and ‘d’ is the depth of water to be irrigated (cm), ‘q’ is the volume of water required to irrigate, 60 is used for unit conversion.

The irrigation water amount (crop water requirement, ETc (mm)) was estimated by the CropWat program for windows using the required data such as crop (kc, growth stage, root depth, critical depletion, yield response factor, crop height, harvest index), daily weather (maximum and minimum temperature, rainfall, wind, humidity, and sunshine hours) all measured at 2 m height), soil (soil texture, total available soil moisture, maximum rain infiltration rate, maximum rooting depth, initial soil moisture depletion, initial available soil moisture, and the study area information (altitude, latitude, longitude).

4. Results

4.1. Maize

In a stage-wise DI study in western Ethiopia, Admasu *et al* (2019) found that moisture stress at different growth stages had a highly significant effect on maize grain yield (table A1). Irrigating maize during all growth stages produced the highest grain yield (8.4 t ha^{-1}). Irrigating maize during all growth stages except the initial stage also produced a high grain yield (7.0 t ha^{-1}). Stressing maize during all growth stages except the initial stage recorded the lowest grain yield (1.0 t ha^{-1}). The highest (2.6 kg m^{-3}) and lowest (0.5 kg m^{-3}) maize WP was attained when irrigating only at the initial stage and at the treatment with full irrigation during all growth stages. Abiyu and Alamirew (2015) also found the highest maize yield (5.9 t ha^{-1}) when full irrigation was applied during all growth stages under Nitisol in northwest Ethiopia. But, a higher WP (1.6 kg m^{-3}) was obtained when 50% DI was applied during development and mid-season growth stages, compared to 75% ETc treated plots at all growth stages (1.3 kg m^{-3}).

In a study by Mengist and Tilahun (2009) in southeast Ethiopia, the highest yield (7.1 t ha^{-1}) was recorded under full irrigation compared with a 75% deficit throughout the growing period, which results in the lowest yield (3.0 t ha^{-1}). When the maize crop received a 75% deficit (25% ETc) during the flowering stage, the effect of the stress was severe as maize is most sensitive to water stress during flowering. Likewise, in central Ethiopia, Admasu *et al* (2019) reported the maximum grain yield (5.5 t ha^{-1}) at fully irrigated fields, followed by 85% ETc (5.2 t ha^{-1}), which was statistically the same. The lowest grain yield (1.5 t ha^{-1}) was found at a 25% ETc treated plot. Seid and Narayanan

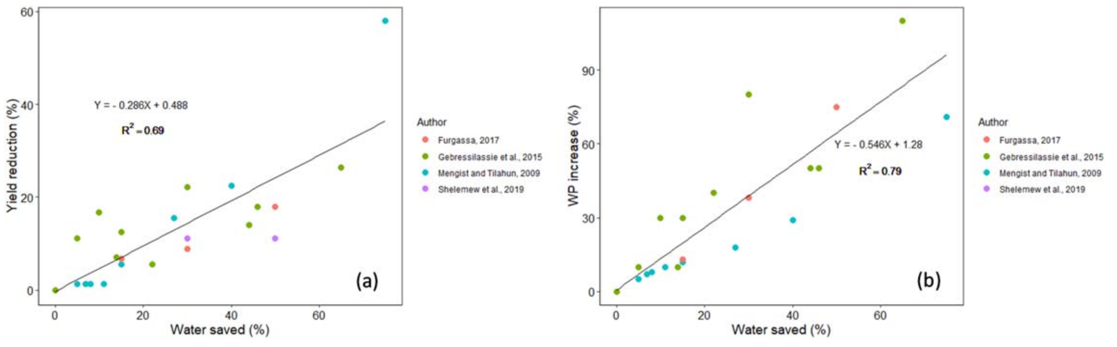

Figure 1. A relationship between maize yield reduction and the percentage of water saved that showing yield reduction increases with increasing water deficit compared with full irrigation water supply (a) and WP increases (%) versus the percentage of water saved (b), N = 4. Values are calculated based on the data taken from the papers mentioned in the legend.

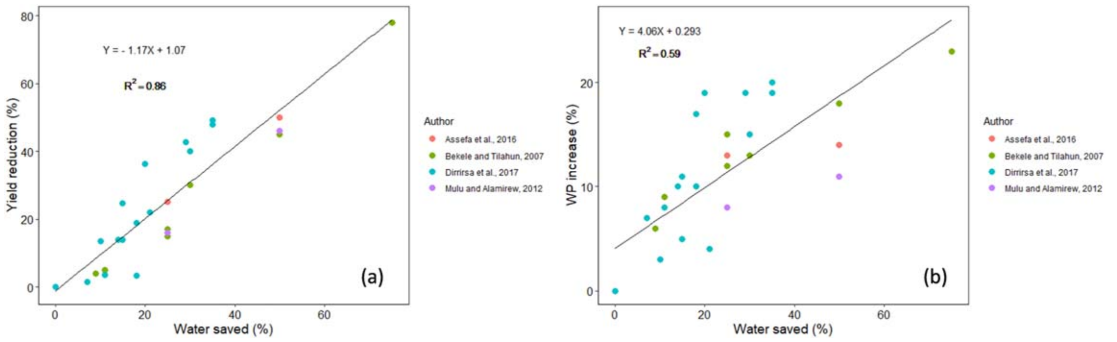

Figure 2. Relationship between onion yield reduction (%) and the percentage of water-saving (a) and WP increases (%) versus the percentage of water-saving (b). Values are calculated based on the data taken from the papers mentioned in the legend. N = 4.

(2015) found the highest (2.1 kg m^{-3}) and the lowest (1.7 kg m^{-3}) WP from alternative furrow irrigation (AFI) at 70% and 100% ETc, respectively. Also, Jemal and Berhanu (2020) in central Ethiopia reported the highest WP (2.4 kg m^{-3}) from the AFI technique compared to conventional furrow irrigation (CFI) (1.6 kg m^{-3}). Yet, this shows an increase in WP under AFI with almost 50%.

A relationship between maize yield reduction and the percentage of water-saving was computed that showed an R^2 of 0.69 (figure 1(a)). The yield reduction of maize increases linearly with a decrease in applied irrigation water relative to full irrigation that meets ETc. In the relationship between maize WP increases (%) and the percentage of water-saving an R^2 of 0.79) was found (figure 1(b)). Reducing the amount of irrigation water by a factor of 4 (25% ETc) results in a maize WP increase of 75%. Similarly, the yield penalty for saving 65% water is 26%, but it results in a 110% increase in WP. This also means that per unit of irrigation water available, 137% more land can be irrigated, or 2.86 ha instead of 1 ha. This results in an overall yield increase of 15.2 t (per 2.8 ha) with the same amount of water, as compared to an overall yield of 7.2 t ha^{-1} with the same amount of water under the full irrigation regime.

4.2. Onion

In a DI study in northern Ethiopia, Bekele and Tilahun (2007) reported the highest (25 t ha^{-1}) and the lowest (5.5 t ha^{-1}) onion yield from fully irrigated (100% ETc) and 25% ETc irrigated plots, respectively (table A2). Enchalew *et al* (2016) and Mulu and Alamirew (2012) also noted comparable findings in northwestern Ethiopia. A DI study done in southern Ethiopia showed that onion bulb yield was affected when the amount of irrigation water was reduced from 100% to 50% ETc (Assefa *et al* 2016). The yield of onion at 75% ETc (25% deficit) was slightly reduced compared with that of 100% ETc irrigated plots. Hence, deficit supplemental irrigation of onion at 75% ETc can be applied to reduce the risks of crop failure in moisture deficit regions.

Compared with farmers' practices (0%) and fixed furrow irrigation (FFI) (37%) strategies, AFI resulted in a WP increment of 74% (Gelu 2018). Also, the application of 25% ETc using AFI raised the overall yield to 90 t per 4 ha compared with FFI, which resulted in 31 t per 1.23 hectare. A study by Temesgen *et al* (2018) in western Ethiopia showed the highest marketable onion yield (43 t ha^{-1}) at the fully irrigated crop (100% ETc). The

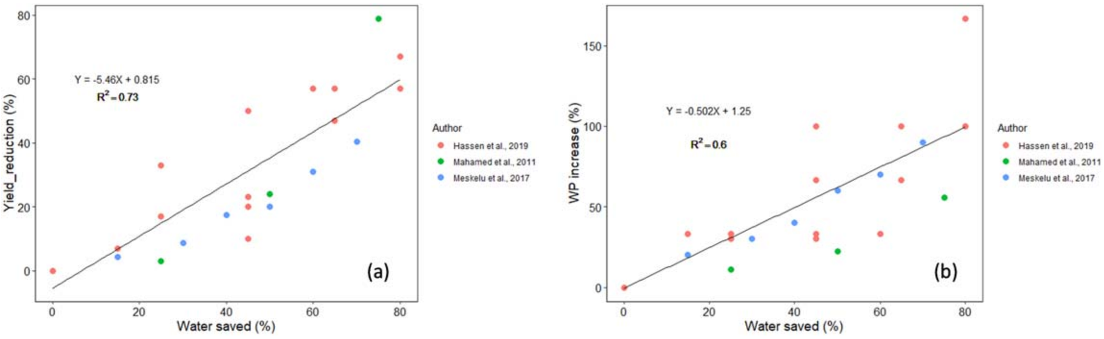

Figure 3. A relationship between wheat yield reduction (%) and the percentage of water-saving (a) and WP increases (%) against the percentage of water-saving (b). Values are calculated based on the data taken from the papers mentioned in the legend. N = 3.

lowest marketable yield (21 t ha^{-1}) was found at 50% ETc treated plots. In a study by Dirirsa *et al* (2017), 100% ETc gave the highest bulb yield (40 t ha^{-1}) with no significant difference from 75% ETc, except when onion was water-stressed at the bulb formation stage. WP decreased from 1.8 kg m^{-3} to 1.3 kg m^{-3} as the application of irrigation water increased from 60% ETc to 100% ETc, respectively. The yield reduction of onion increases linearly with increasing water stress (figure 2(a)). The regression analysis done between yield reduction and water-saving yielded an R^2 value of 0.86. Yet, a clear increasing onion WP increment with decreasing water supply was found with an R^2 value of 0.59 (figure 2(b)). Decreasing the amount of irrigation water with a factor of 4 (25% ETc) results in a WP increase of 32%. The yield penalty for saving 75% water is only 5%, but it results in an overall yield of 90 t per 4 ha, as 300% more land can be irrigated with the same amount of water. In comparison, under the full-irrigation regime, with the same amount of water the overall yield is 22.5 t ha^{-1}.

4.3. Wheat

In a stage-wise DI study in central Ethiopia, Meskelu *et al* (2017) reported the highest (4.6 t ha^{-1}) and the lowest (2.7 t ha^{-1}) wheat grain yield from 100% and 30% ETc, respectively (table A3). The maximum WP (1.8 kg m^{-3}) was recorded at 30% ETc. A rather similar value was found with irrigation use of 40% ETc. On the other hand, the lowest WP (1.1 kg m^{-3}) was obtained at 100% ETc and this was statistically similar with 85% ETc. In a wheat response to a stage-wise DI study from southeastern Ethiopia, Hassen *et al* (2019) found the highest grain yield (3 t ha^{-1}) at full irrigation, which was similar to yields of other DI strategies that irrigated at all stages except the initial stage (2.9 t ha^{-1}), and irrigation of all stages except maturity (2.8 t ha^{-1}) stages. This means that DI application at less water stress-sensitive growth stages could be an option to increase overall yield and WP with the same amount of water with a very small yield reduction. Mahamed *et al* (2011) reported the highest WP (1.4 kg m^{-3}) at 25% ETc treated plots compared with 100% ETc (0.9 kg m^{-3}). The application of 50% ETc resulted in an overall yield increment of 5 t per 2 hectares while the overall yield at 100% ETc is 3.3 t ha^{-1}. The wheat yield reduction increases linearly with increasing water deficit. An R^2 of 0.73 was found in the calculated relationship between yield reduction and the percentage of water-saving (figure 3(a)). Yet, the wheat WP increment increases with decreasing water supply in all studies mentioned (figure 3(b)), showing a linear relationship with an R^2 of 0.6). Declining the amount of irrigation water by a factor of 3.33 (30% ETc) results in a wheat WP increase of 90%. The yield reduction for saving 70% water is 40%, still, it increases the overall yield of 9 t per 3.33 ha (irrigating about 233% more land with the same amount of water). Yet, under the full-irrigation regime, the overall yield is 2.7 t ha^{-1} with the same amount of water.

4.4. Tomato

In a DI study on tomatoes in southern Ethiopia, Kifle (2018) obtained a maximum yield of 32 t ha^{-1} at full irrigation compared to 85% ETc (25 t ha^{-1}) and 70% ETc (23 t ha^{-1}) DI strategies (table A4). A treatment receiving 100% ETc has a 7.0% and 15% yield increment compared to 75 and 50% ETc water supply, respectively, while the statistical analysis showed that use of 100% ETc had a significant yield difference with 50% ETc but similar with that of 75% ETc water supply. In central Ethiopia, Etissa *et al* (2014) found a marketable yield of 64 t ha^{-1} at full irrigation and 27.8 t ha^{-1} under 60% ETc. Similarly, Birhanu and Tilahun (2010) stated a significant decrease in marketable yield from 47 t ha^{-1} to 15 t ha^{-1} with 100% and 25% ETc, respectively. The marketable yield of tomatoes was the lowest at 25% ETc. Also in southern Ethiopia, Habtewold and Gelu (2019) found a maximum of 32 t ha^{-1} and a minimum of 19 t ha^{-1} marketable yield at 100% and 50% ETc water applications, respectively. It was found that the use of 50% and 70% of ETc did not significantly affect the marketable yield of tomatoes. The highest WP (7.0 kg m^{-3}) was achieved at 50% of ET_C compared to 100%

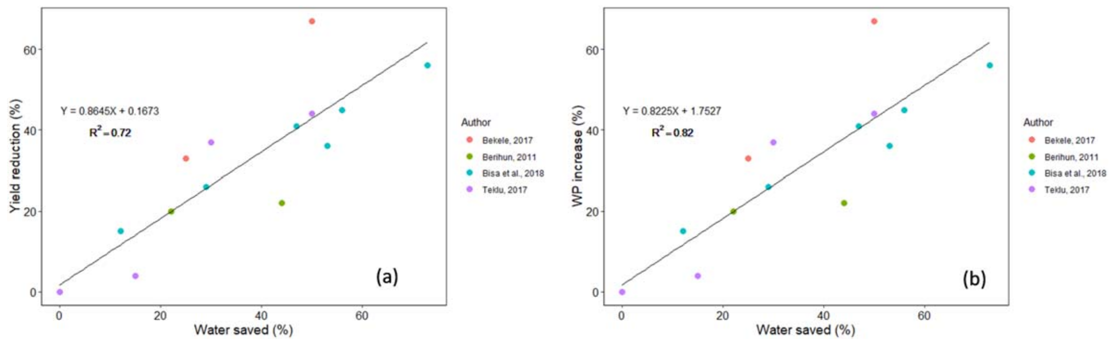

Figure 4. A relationship between tomato yield reduction (%) versus the percentage of water-saving (%) for irrigated tomato (a) and WP increases (%) against saved water (%) showing a strong positive relationship (b). Values are calculated based on the data taken from the papers mentioned in the legend. N = 4.

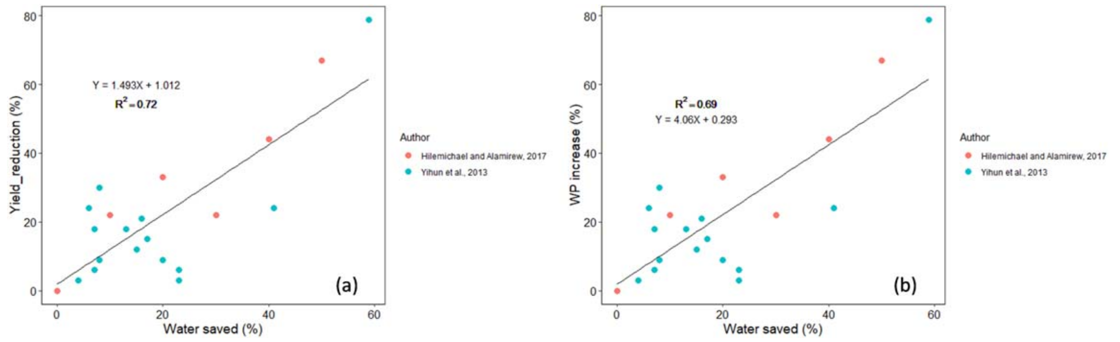

Figure 5. A relationship between teff yield reduction (%) and the percentage of water-saving (a) and Teff WP increases (%) against saved water (%) (b). Values are calculated based on the data taken from the papers mentioned in the legend. N = 2.

ETc although there was no significant difference among treatments. Bekele (2017) and Berihun (2011) also reported comparable findings for tomatoes.

As the case in other crops, the tomato yield reduction increased linearly with increasing water deficit (water-saving). The relationship ($R^2 = 0.72$) between yield reduction and the percentage of water saved was calculated (figure 4(a)). But, an increase in tomato WP increment with declining water supply was noticed (figure 4(b)). The regression analysis between WP increment and the percentage of water-saved showed an R^2 of 0.82.

Reducing the amount of irrigation water by a factor of 2 (50% ETc) results in a tomato WP increase of 67%. The yield decline for saving 50% water is only 18%, but, it results in an overall yield increase of 94 t per 2 ha (100% more land could be irrigated with the same amount of water). But, under the full-irrigation regime, the overall yield remains 47 t ha^{-1} with the same amount of water.

4.5. Teff

A DI study on teff WP was conducted by Yihun *et al* (2013) in central Ethiopia. The maximum grain yield (3.3 t ha^{-1}) was obtained at 100% ETc and the lowest (0.6 t ha^{-1}) at 25% ETc during the whole growing season, respectively (table A5). However, there were no substantial yield differences between 100% ETc and 75% ETc water applied all over the growing period. In a field experiment in southeast Ethiopia, Hilemicael and Alamirew (2017) found the highest (2 kg m^{-3}) teff biomass WP at a 50% ETc irrigation water supply compared with 100% ETc (1.3 kg m^{-3}). The yield reduction of teff and the percentage of water-saved showed an R^2 of 0.72, figure 5(a). Also, the regression analysis showed an increasing teff WP increment with lessening water supply with an R^2 value of 0.69 (figure 5(b)). Decreasing the amount of irrigation water by a factor of 1.25 (80% ETc) results in a teff WP increase of 11%. Similarly, the yield penalty for saving 20% water is only 3%, nevertheless, it results in an increased overall yield of 4.3 t per 1.25 ha with the equivalent amount of water. But, under the full-irrigation regime, the overall yield remains 3.2 t ha^{-1} with the same amount of water.

5. Discussion

Irrespective of the amount of water deficit, the application of DI during the whole growing season reduced maize yield as compared with the yield obtained under full irrigation (Abiyu and Alamirew 2015). But, a 25% water deficit during the initial and development stages as compared with full irrigation resulted in a minimum yield reduction of 6%. Alternative furrow irrigation (AFI) increased water productivity (WP) compared with conventional furrow irrigation (Seid and Narayanan 2015, Jemal and Berhanu 2020). The reason for having high WP and lower yield reduction under AFI could be related to better water distribution within the reach of roots on both sides of the ridges. Mengist and Tilahun (2009) also reported the highest (1.8 kg m^{-3}) and the lowest maize WP (1.0 kg m^{-3}) at 75% and 100% ETc, respectively. Perhaps, reducing the amount of water application (ETc) and stressing the plant at low moisture stress-sensitive phenological stages could enable farmers to save more water without much yield decline, an increase in irrigated area, and higher WP and overall yield increase. This is more desirable when crop failures will happen due to prolonged dry spells. We have also noticed an improved maize yield due to increasing soil fertility conditions combined with water management. For instance, Erkossa *et al* (2011b) found that the grain yield of maize increased from 2.5 t ha^{-1} in poor to 6.4 and 9.2 t ha^{-1} with closely optimal and non-limiting soil fertility conditions with an equal amount of water. Consistently, soil evaporation declined, while transpiration and thus biomass production increased. As a result, WP increased by 48% and 54%, respectively, with the closely optimal and non-limiting soil fertility conditions.

The application of 75% ETc at all growth stages and stressed at the initial stage improved the WP of the onion by 13% compared to full irrigation (Bekele and Tilahun 2007). Enchalew *et al* (2016) and Mulu and Alamirew (2012) also reported comparable findings for onion from the central Rift Valley region and northwest Ethiopia, respectively. Applying 50% ETc using the AFI technique increased onion WP by 74% and overall yield by 58% without yield reduction compared with farmer's practices (FP) (Gelu 2018). This amount of water is enough to irrigate an extra 1.2 ha of onion cropland using the AFI technique that can earn better economic returns compared to that of FP. It is possible to say that onion bulb production is highly sensitive to moisture stress during the development and bulb formation stages, whereas the establishment and ripening stages are less sensitive to moisture stress.

The application of 85% and 70% of ETc DI strategies didn't show a significant wheat yield decline (Meskelu *et al* 2017). The decline of water from 100 to 30% ETc led to the raising of WP by 72%. The lower WP recorded at 100% ETc may be due to higher water consumption, much of which was lost through soil water evaporation, runoff, and deep percolation. Other studies have shown that DI significantly increased WP compared to rain-fed wheat (Moser *et al* 2006; Ersel *et al* 2010). Mirzaei *et al* (2011) also found that drought stress at flowering and grain filling stages induced 32% and 35% yield reduction compared with fully irrigated plots, respectively. The minimum grain yield (0.9 t ha^{-1}) was recorded when irrigated only at the maturity stage (Hassen *et al* 2019) compared with the yield gained at fully irrigated (3.0 t ha^{-1}). Consistently, these results agreed with those reported by Ersel *et al* (2010), Moser *et al* (2006), and Stone *et al* (2001) who stated that with increasing moisture stress, the dry matter production of the crop decreases directly by decreasing cell division, and enlargement, and indirectly by reducing the rate of photosynthesis. Moderately water deficits could significantly improve the fruit quality of tomato (size, shape, juiciness, and color of the fruit) without depressing marketable yields with fully irrigated treatments, while dry matter content (solids) and acid content were reduced (Birhanu and Tilahun 2010). The decrease in solids will lower the fruit quality for processing. A prolonged water deficit also led to fruit cracking. In choosing the irrigation practices, attention must, therefore, be given to the type of essential end product. The use of 70% and 50% of ETc didn't significantly affect the marketable yield of tomatoes (Habtewold and Gelu 2019). Kifle (2018) found a higher WP value with a significant difference at 50% ETc compared with full irrigation. Bekele (2017) and Berihun (2011) also reported comparable findings. Related findings also stated for the same crop in other areas suggested that the adoption of DI strategies in which some reduction in irrigation dose for the whole or part of the growing season helped to minimize fruit losses of tomato and maintain high fruit quality (Topcu *et al* 2006, Patane *et al* 2015).

Teff is very sensitive to water stress during the mid-season stage. Even when it is only subjected to a 25% deficit, its yield decreased by about 1 t ha^{-1} (Yihun *et al* 2013). Stressing the crop either by 50% or 75% at the mid-season stage results in lower yields. But, the highest WP (1.1 kg m^{-3}) was thus, found at 50% stress throughout the whole growth stage compared to a 75% deficit (0.4 kg m^{-3}). Yihun (2015) also stated comparable findings for teff from the same study area with the same climate and soil. It was also found that a 50% reduction in the amount of irrigation water increased the WP of teff by 54% (Hilemicael and Alamirew 2017). The application of 45 mm water as supplementary irrigation only at the flowering stage increased the teff yield by 50%–168% for late sowing and 16%–75% for early sowing in northern Ethiopia (Tsegay *et al* 2015). In the same region, Araya *et al* (2011) found increased WP of teff when supplementary irrigation applied after the start of flowering increased from 0 to 95 mm. Araya *et al* (2010) also reported a higher WP for teff when 90% of the optimal water need of the crop was met. Thus, applying DI at less stress-sensitive stages would improve WP without considerable yield loss and increase overall yield via expanding irrigated areas which could be irrigated by the saved water from DI application.

6. Opportunities and constraints of adopting DI in Ethiopia

6.1. Opportunities

Though DI results in some yield reductions per hectare, the quality of the product (e.g. sugar content, grain size) is likely to be equal or even higher than under full irrigation (Kirda *et al* 2005, Moser *et al* 2006). DI can create reduced humid conditions around the crop in comparison with over-irrigation/full irrigation, reducing the effect of fungal diseases. Lowering irrigation water depth over the crop cycle will also decline agrochemical and nutrient losses through leaching from the root zone, reduce the fertilizer needs of the crop, and improves groundwater quality (Kirda *et al*2005, Moser *et al* 2006). The other advantage of DI is the improvement of WP and increases in the overall yield of all crops due to expanding the irrigated area, irrigating by the saved water.

Over-dose use of fertilizer may cause crops to be more susceptible to dry spells and may lead to reduced harvest indexes (Tari 2016). Conversely, over-dose fertilizer use only results in a higher yield if sufficient N-fertilizer is applied (Geerts *et al* 2008a). This indicates that each DI strategy has an optimum fertilizer amount (Steenbergen *et al* 2004). Thus, DI is best effective if diverse soil and other related field managements are considered side by side. What is frequently considered as the win-win effect of DI and decreased fertilizer use (Moser *et al* 2006) is the fact that combining DI and optimum fertilizer application leads to a higher yield increase than the sum of the separate yield increases obtained by both factors.

The other merit of DI is the possibility of controlling sowing dates by irrigation, which allows the implementation of improved agricultural practices (Oweis and Hachum 2012). For example, if a common irrigation strategy is adopted in a region, peaks in irrigation water supply will occur during drought-sensitive stages. This might result in under-irrigation of land at the tail end of the irrigation network, causing more severe yield reductions than anticipated. DI strategies would be more efficient if it is combined with integrated soil management practices. Different works have been done on the effect of DI on yield and WP. But, there is no literature regarding the effect of DI integrated with soil management strategies like soil fertility, acidity, and salinity management on yield and WP. Hence, field-level researches that combined DI with integrated soil management strategies are needed to sustainably advance WP and yield in the face of limited water supply.

6.2. Constraints

Despite the various benefits, DI involves many constraints that hindered its adoption and scale-up to wider communities. Among other problems, the knowledge gap about DI is the most important one. Understanding the crop response to drought stress is a precondition for DI application (Geerts and Raes 2009), hence, applying DI without the awareness of crop response to water stress can significantly affect yield and WP.

DI can only be effective if actions are taken to avoid salinization. By using DI strategies, over-irrigation rarely occurs. Therefore, the leaching of salts from the root zone is lower under DI than under full irrigation (Hsiao *et al* 2007). This is mostly observed in arid and semi-arid areas where water is scarce coupled with hot temperatures (Fereres and Soriano 2007), which may affect the sustainability of irrigation projects. For instance, 10–15 years ago, a privately owned irrigation project was completely abandoned due to salinization in the Rift Valley region of Ethiopia. This was because the rainfall in that area was not sufficient to provide the leaching requirement to remove an excess of salts accumulated in the crop root zone as ET usually removes the water leaving the precipitated salts on the surface. Therefore, the application of DI without taking protective measures to periodically perform the leaching of concentrated salts poses a problem for the sustainability of irrigation farming.

According to Zwart and Bastiaanssen (2004), the major challenges that affect the application of DI can be summarized as (i) technical constraints, (ii) lack of knowledge on better and diversified irrigation agronomic practices, (iii) insufficient baseline data and information on the development of water resources, (iv) inadequate experience in design, construction and supervision of quality irrigation projects, (v) poor performance of existing irrigation schemes, (vi) lack of community contribution during planning, construction and use of irrigation development, and (vii) lack of capital for irrigation infrastructure development are some of them to mention.

7. Conclusion and recommendations

The main objective of DI is to increase the WP of a crop by reducing irrigations that have little impact on yield. The percentage of water-saved versus WP increase as well as the percentage of water-saved versus overall yield increment for the studied crops were positively correlated. DI strategies have demonstrated the possibility of attaining optimum yields by allowing a certain level of yield loss per hectare but higher returns gained from irrigating extra land by the saved water. Decide what deficit level to allow, when not to allow a deficit to occur, and when to apply water at a lower level of adequacy, thus, increasing the marketable yield of the crops for each unit of water transpired and achieve the highest WP. For instance, for most crops, imposing water stress during the mid-season growing stage gave the lowest yield, indicating the severe effect of water stress during the flowering and grain filling stage. With growing water scarcity and increasing competition for water, there will be more widespread adoption of DI, especially in arid and semi-arid regions. While there are enormous prospects to adopt DI, it has been struggling with many problems such as information gaps, practical problems, improper water management strategies, and more risk of soil salinity. This study could contribute to the advancement of improving the water productivity of crops under high water competition by providing yield penalty, overall yield increase by irrigating extra land using the saved water, water productivity increment, and water saved information due to DI application. In conclusion, in areas where soil moisture is the limiting factor for crop production and adequate arable land is available, the application of DI is promising.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

This is to confirm that there is no potential conflict of interest.

Annex

Table A1. Water saved (%), yield (t ha^{-1}), yield reduction (%), overall yield increase (t ha^{-1}), water productivity (kg m^{-3}), and water productivity increment (%) of maize under different deficit irrigation strategies conducted in a different part of Ethiopia .

Study	Applied irrigation water (ETc %)	Water saved (%)	Yield t ha^{-1}	Yield reduction(%)	Overall yield increase (t ha^{-1})	WP kg m^{-3}	WP increment (%)	Texture
Admasu *et al* 2017	Irrigated all stages	0	8.4	0	8	0.5	—	Clay loam
	Irrigated all stages except I	27	6.9	18	10	0.6	14	
	Irrigated all stages except D	54	4.4	48	10	0.6	14	
	Irrigated all stages except L	61	4.6	45	16	0.9	90	
	Irrigated all stages except M	64	5.7	32	16	0.9	88	
	Irrigated all stages except I & D	61	4.7	44	16	1	94	
	Irrigated all stages except I & L	75	5.4	36	22	1.3	156	
	Irrigated all stages except I & L	62	5.4	36	14	0.8	40	
	Irrigated all stages except D & M	75	3	64	12	0.7	44	
	Irrigated all stages except D & M	75	3.5	58	14	0.8	64	
	Irrigated all stages except L & M	75	4.1	51	16	1.8	268	
	Irrigated only at M stage	85	3.2	62	21	1.4	170	
	Irrigated only at L stage	81	3.9	54	21	1.2	144	
	Irrigated only at D stage	90	3.8	55	38	2.3	358	
	Irrigated only at I stage	95	1.8	79	36	2.7	430	
Abiyu and Alamirew 2015	Irrigated all stages	0	5.8	0	6	1.4	—	Clay
	Irrigated all stages except I & D	7	5.5	5	6	1.5	0.7	
	Irrigated all stages except M & L	36	4	31	6	1.5	5	
	Irrigated all stages except D & M	37	4.3	26	7	1.7	15	
	Irrigated 50% ETc at all stages	50	2.8	52	6	1.4	−6	
	Irrigated 25% ETc at all stages	75	1.3	78	5	1.3	−10	
Mengist and Tilahun 2009	Irrigated all stages	0	7.1	0	7	1.0	—	Clay loam
	Irrigated 25% ETc at all stages	75	3	58	12	1.8	71	
	Irrigated all stages except I	8	7	1	8	1.1	8	
	Irrigated all stages except D	15	6.7	6	8	1.2	12	
	Irrigated all stages except M	40	5.5	23	9	1.3	29	
	Irrigated all stages except L	11	7	1	8	1.1	10	
	Irrigated all stages except I	5	7	1	7	1.1	5	
	Irrigated all stages except D	11	7	1	8	1.1	10	
	Irrigated all stages except M	27	6	16	8	1.2	18	
	Irrigated all stages except L	7	7	1	8	1.1	7	
Seid and Narayanan 2015	100	0	8	0	8	1.7	—	Clay loam
	85	15	7	13	8	1.9	12	
	70	30	6	25	9	2	18	
	50	50	6	25	12	2	18	

Table A1. (Continued.)

Study	Applied irrigation water (ETc %)	Water saved (%)	Yield t ha^{-1}	Yield reduction(%)	Overall yield increase (t ha^{-1})	WP kg m^{-3}	WP increment (%)	Texture
Jemal and Berhanu 2020	100% ETc using CFI	0	9	0	9	2.2	—	Sandy clay loam
	50% ETc using AFI	50	6.7	26	13	2.4	13	
	50% ETc using FFI	50	5.9	34	12	1.6	24	
Admasu *et al* 2019	100	0	6	0	6	0.7	—	Clay loam
	85	15	5	17	6	0.8	14	
	75	25	5	17	7	0.8	14	
	65	35	4	33	6	0.7	0	
	55	45	4	33	7	0.8	14	
	45	55	3	50	7	0.8	14	
	35	65	2	67	4	0.9	29	
	25	75	1.5	78	6	1	30	
Shelemew *et al* 2019	100	0	4.5	0	5	0.8	—	Loam
	85	15	4.2	7	5	0.9	13	
	70	30	4	11	6	1.1	38	
	50	50	4	11	8	1.4	75	
Furgassa 2017	100	0	4.5	0	5	0.8	—	Loam
	85	15	4.2	7	5	0.9	13	
	70	30	4.1	9	6	1.1	38	
	50	50	3.7	18	7	1.4	75	
Gebressilassie *et al* 2015	100	0	7.2	0	7	1	—	Clay
	95	5	6.4	11	7	0.9	10	
	90	10	8.4	−17	9	1.3	30	
	86	14	6.7	7	8	1.1	10	
	85	15	8.1	−13	10	1.3	30	
	78	22	7.6	−6	10	1.4	40	
	70	30	8.8	−22	13	1.8	80	
	56	44	6.2	14	11	1.5	50	
	54	46	5.9	18	11	1.5	50	
	35	65	5.3	26	15	2.1	110	

Where: I = Initial stage, D = Development stage, M = mid-season stage, L = maturity stage; 100% ETc indicates optimum/full watering (0% deficit); 75% ETc indicates watering 75% ETc (25% deficit); 50% ETc means watering 50% of ETc watering (50% deficit); 25% ETc indicates watering only 25% of ETc (75% deficit) and it continues like these for other deficit treatments; water productivity (WP). Values written in italics are calculated from papers mentioned in the legend.

Table A2. Water saved (%), yield (t ha^{-1}), yield reduction (%), overall yield increase (t ha^{-1}), water productivity (kg m^{-3}), and water productivity increment (%) of onion as affected by deficit irrigation strategies conducted in a different part of Ethiopia .

Study	Applied irrigation water (ETc %)	Water Saved (%)	Yield t ha^{-1}	Yield reduction (%)	Overall yield increase (t ha1)	WP kg m^{-3}	WP increment(%)	Texture
Bekele and Tilahun 2007	100% ETc irrigated all stages	0	25	0	25	9	0	clay loam
	90 irrigated all stages but stressed at I	9	24	4	26	10	6	
	89% irrigated at all stages but stressed at I stage	11	23.9	5	27	10	9	
	75% irrigated at all stages but stressed at M stage	25	21.3	15	28	10	15	
	75% irrigated at all stages but stressed at F stage	25	20.8	17	28	10	13	
	70% irrigated at all stages but stressed at D stage	30	17.5	30	25	9	13	
	50% irrigated at all stages throughout the season	50	13.8	45	28	10	18	
	25% irrigated at all stages throughout the season	75	5.5	78	22	8	23	
Enchalew *et al* 2016	100	0	11	0	11	2	2	Clay loam
	90	10	9	18	10	2	4	
	80	20	8	27	10	2	4	
	70	30	8	27	11	3	9	
	60	40	7	36	12	2	4	
	50	50	6	45	12	2	4	
Mulu and Alamirew 2012	100	0	40	0	40	5	—	Clay
	75	25	34	16	45	6	8	
	50	50	22	46	44	6	11	
Assefa *et al* 2016	100	0	21	0	21	3	—	Sandy loam
	75	25	17	25	23	4	33	
	50	50	8	50	16	4	33	
Gelu 2018	100% ETc (FP)	0	21.4	0	21	2	—	Clay loam
	81% ETc (FFI)	19	25	−17	31	3	37	
	50% ETc (AFI)	50	29	−36	58	3	74	
	25% ETc AFI	75	22.5	−5	90	3	32	
Temesgen *et al* 2018	100% ETc irrigated all stages	0	43	0	43	8	0	Clay
	Irrigated 75% ETc at D, L, M except I	33	39.1	8	58	11	38	
	Irrigated 75% ETc at I, L, M except D	40	33.3	20	56	10	25	
	Irrigated 75% ETc at I, D, L except M	51	27	33	55	11	38	
	Irrigated 75% ETc at I, D, M except L	50	35	16	70	13	63	
	Irrigated 50% ETc at D, L, M except I	56	28.4	30	65	12	50	
	Irrigated 50% ETc at I, L, M except D	60	23.7	40	59	12	50	
	Irrigated 50% ETc at I, D, L except M	67	21	45	63	13	63	
	Irrigated 50% ETc at I, D, M except L	67	25.3	36	77	15	88	
Dirirsa *et al* 2017	100% ETc irrigated all stages	0	40.4	0	40	10	0	
	Irrigated all stages but 25% deficit at D	7	39.9	1	43	11	7	

Table A2. (Continued.)

Study	Applied irrigation water (ETc %)	Water Saved (%)	Yield t ha^{-1}	Yield reduction (%)	Overall yield increase (t ha1)	WP kg m^{-3}	WP increment(%)	Texture
	Irrigated all stages but 25% deficit at B	10	35	14	39	10	3	Clay loam
	Irrigated all stages but 50% deficit at D	15	34.5	14	41	11	5	
	Irrigated all stages but 50% deficit at B	20	25.9	36	32	8	19	
	Irrigated all stages but 25% deficit at I & D	11	39	4	44	11	8	
	Irrigated all stages but 25% deficit at D & B	18	32.9	19	40	10	1	
	Irrigated all stages but 25% deficit at B & M	14	34.5	14	40	10	1	
	Irrigated all stages but 50% deficit at I & D	21	31.7	22	40	10	4	
	Irrigated all stages but 50% deficit at D & B	35	20.8	49	32	8	20	
	Irrigated all stages but 50% deficit at B & M	29	23.4	43	33	8	19	
	25% deficit at I, D & M stages	18	39	3	48	12	17	
	25% deficit at I, B & M stages	15	30.6	25	36	9	11	
	50% deficit at I, D & M stages	30	24.2	40	35	9	15	
	50% deficit at I, B & M stages	35	21.3	48	33	8	19	

Where: AFI = alternative furrow irrigation, FFI = fixed furrow irrigation, 50% alternative furrow irrigation, FP = farmers practice, I = Initial stage, D = Development stage, M = mid-season stage, L = maturity stage; 100% ETc indicates optimum/full watering (0% deficit); 75% ETc indicates watering 75% ETc (25% deficit); 50% ETc means watering 50% of ETc watering (50% deficit); 25% ETc indicates watering only 25% of ETc (75% deficit) and it continues like for other deficit treatments. Values written in italics are not directly taken from studies rather calculated.

Table A3. Water saved (%), yield (t ha^{-1}), yield reduction (%), overall yield increase (t ha^{-1}), water productivity (kg m^{-3}), and water productivity increment (%) of wheat as affected by DI strategies conducted in a different part of Ethiopia .

Study	Applied irrigation water (ETc %)	Water saved (%)	Yield t ha^{-1}	Yield reduction (%)	Overall yield increase (t ha^{-1})	WP kg m^{-3}	WP increment (%)	Texture
Meskelu *et al* 2017	100	0	4.6	0	5	1	—	Clay loam
	85	15	4.4	4	5	1.2	20	
	70	30	4.2	9	6	1.3	30	
	60	40	3.8	17	6	1.4	40	
	50	50	3.7	20	7	1.6	60	
	40	60	3.2	31	8	1.7	70	
	30	70	2.7	40	9	1.9	90	
Mahamed *et al* 2011	100	0	3.3	0	3	0.9	—	Loam
	75	25	3.2	3	4	1	11	
	50	50	2.5	24	5	1.1	22	
	25	75	0.7	79	3	1.4	56	
Hassen *et al* 2019	100% ETc irrigated in all stages	0	3	0	3	0.3	—	Silt
	85% ETc irrigated in all stages except I	15	2.9	7	3	0.4	33	
	75% ETc irrigated in all stages except D	25	2.5	17	3	0.4	33	
	75% ETc irrigated in all stages except M	25	1.9	33	3	0.3	0	
	85% ETc irrigated in all stages except L	15	2.8	7	3	0.4	33	
	55% ETc irrigated in I & D	45	1.5	50	3	0.3	0	
	55% ETc irrigated in I & M	45	1.5	50	3	0.4	33	
	55% ETc irrigated in I & L	45	2.7	10	5	0.6	100	
	40% ETc irrigated in D & M	60	1.3	57	3	0.4	33	
	55% ETc irrigated in D & L	45	2.4	20	4	0.6	100	
	55% ETc irrigated in M & L	45	2.3	23	4	0.5	67	
	20% ETc irrigated only at L	80	0.9	67	5	0.6	100	
	35% ETc irrigated only at M	65	1.3	57	4	0.5	67	
	35% ETc irrigated only at D	65	1.6	47	5	0.6	100	
	20% ETc irrigated only at I	80	1.3	57	7	0.8	167	

Where: I = Initial stage, D = Development stage, M = mid-season stage, L = maturity stage; 100% ETc indicates optimum/full watering (0% deficit); 75% ETc indicates watering 75% ETc (25% deficit); 50% ETc means watering 50% of ETc watering (50% deficit); 25% ETc indicates watering 25% of ETc (75% deficit) and it continues like these for other deficit treatments. Values written in italics are not directly taken from studies rather calculated.

Table A4. Water saved (%), yield (t ha^{-1}), yield reduction (%), overall yield increase (t ha^{-1}), water productivity (kg m^{-3}), and water productivity increment (%) of tomato as affected by deficit irrigation strategies conducted in a different part of Ethiopia .

Study	Applied irrigation water (ETc %)	Water saved (%)	Yield t ha^{-1}	Yield reduction (%)	Overall yield increase (t ha^{-1})	WP kg m^{-3}	WP increment (%)	Texture
Kifle 2018	100	0	32	0	32	8.2	—	Clay
	85	15	25	22	30	12	44	
	70	30	23	28	33	11	34	
	50	50	23	28	46	11	34	
Etissa *et al* 2014	100	0	64	0	64	29	—	Clay loam
	80	20	34	17	43	24	17	
	60	40	28	0	47	29	0	
Birhanu and Tilahun 2010	100% ETc	0	47	0	47	7.4	—	Loam
	Irrigated all stages except I	12	35	4	45	6.2	16	
	Irrigate all stages except D	29	27	43	38	6	19	
	Irrigate all stages except M	35	40	15	62	9.6	30	
	Irrigate all stages except F	35	39	17	60	9.5	28	
	Irrigate all stages except I & D	38	29	60	47	5	32	
	Irrigate all stages except I & M	30	37	21	53	8.2	11	
	Irrigate all stages except D & M	64	29	38	63	13	76	
	Stress I, D, & F stages	75	15	68	60	9	22	
Habtewold & Gelu 2019	100	0	32	0	0	7	0	Clay
	85	15	25	22	30	7	1.5	
	75	25	23	28	31	7	3	
	50	50	23	28	46	7	3	
Bekele 2017	100 (CFI)	0	57	0	57	9	0	Clay
	75 (CFI)	25	53	7	71	11	33	
	50 (CFI)	50	47	18	94	15	67	
Berihun 2011	100	0	54	0	54	10	0	Clay
	78	22	52	4	67	12	20	
	56	44	41	24	73	12	22	

Where: I = Initial stage, D = Development stage, M = mid-season stage, L = maturity stage; 100% ETc indicates optimum/full watering (0% deficit); 75% ETc indicates watering 75% ETc (25% deficit); 50% ETc means watering 50% of ETc watering (50% deficit); 25% ETc indicates watering only 25% of ETc (75% deficit) and it continues like for other deficit treatments. Values written in italics are not directly taken from studies rather calculated. CFI is conventional furrow irrigation; F is the flowering stage, Values written in italics are not directly taken from studies rather calculated.

Table A5. Water saved (%), yield (t ha^{-1}), yield reduction (%), overall yield increase (t ha^{-1}), water productivity (kg m^{-3}), and water productivity increment (%) of tef as affected by deficit irrigation strategies conducted in a different part of Ethiopia .

Study	Applied irrigation water (ETc%)	Water saved (%)	Yield t ha^{-1}	Yield reduction (%)	Overall yield increase (t ha^{-1})	WP kg m^{-3}	WP increment (%)	Texture
Yihun *et al* 2013	100% irrigated at all stages	0	3.3	0	3	0.9	—	
	75% irrigated at all stages	25	3.2	3	4	1	11	
	50% irrigated at all stages	50	2.5	24	5	1	24	
	25% irrigated at all stages	75	1.7	49	4.1	0.4	56	Clay loam
	75% irrigated at I stage	15	2.9	12	12	1	11	
	75% irrigated at D stage	7	2.7	18	11	0.9	0	
	75% irrigated at M stage	8	2.3	30	9	0.7	4	
	75% irrigated at L stage	4	3.2	3	12	0.9	0	
	50% irrigated at I stage	20	3	9	6	1	11	
	50% irrigated at D stage	13	2.7	18	5	0.8	11	
	50% irrigated at M stage	6	2.5	24	5	0.7	11	
	50% irrigated at L stage	7	3.1	6	6	0.9	0	
	25% irrigated at I stage	23	3.1	6	4	1	11	
	25% irrigated at D stage	17	2.8	15	4	0.9	0	
	25% irrigated at M stage	16	2.6	21	34	0.7	4	
	25% irrigated at L stage	8	3	9	4	0.8	11	
Hilemichael and Alamirew 2017	100	0	0.9	—	0.9	1.3	—	
	90	10	0.7	22	0.7	1.4	7.7	
	80	20	0.6	33	0.8	1.6	23	Loam
	70	30	0.7	22	1	1.7	30	
	60	40	0.5	44	0.8	1.9	46	
	50	50	0.3	67	0.6	2	54	

Where: I = Initial stage, D = Development stage, M = mid-season stage, L = maturity stage; 100% ETc indicates optimum/full watering (0% deficit); 75% ETc indicates watering 75% ETc (25% deficit); 50% ETc means watering 50% of ETc watering (50% deficit); 25% ETc indicates watering only 25% of ETc (75% deficit) and it continues like for other deficit treatments. Values written in italics are not directly taken from studies rather calculated.

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References

Abiyu A and Alamirew T 2015 Assessment of stage-wise deficit furrow irrigation application on maize production at koga irrigation scheme, Blue Nile River Basin, Ethiopia *J. Economics and Sus. Dev.* **21** 21–9

Admasu R, Tadesse M and Shimbir T 2017 Effect of growth stage moisture stress on maize (Zea Mays L) yield and water use efficiency at West Wellaga, Ethiopia *Journal of Biology, Agriculture and Healthcare* **7** 98–103

Admasu R, W/Michael A and Hordofa T 2019 Effect of moisture stress on maize (Zea Mays L.) yield and water productivity *Int. J. Environ. Sci. Nat. Res.* **16** 001–005

Ali M H and Talukder M S U 2007 Increasing water productivity in crop production. A synthesis *Agric. Water Manag.* **95** 1201–13

Allen R, Pereira S, Raes D and Smith M 1998 Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56 *Water Resources, Development and Management Service* (Food and Agriculture Organization of the United Nations Rome)

Ambachew S, Alamirew T and Melese A 2014 Performance of mungbean under deficit irrigation application in the semi-arid highlands of Ethiopia *Agric. Water Manag.* **136** 68–74

Araya A, Habtu S, Hadgu K M, Kebede A and Dejene T 2010 Test of AquaCrop model in simulating biomass and yield of water-deficient and irrigated barley (Hordeum vulgare) *Agric. Water Manag.* **97** 1838–46

Araya A, Stroosnijder L, Girmay G and Keesstra S D 2011 Crop coefficient, yield response to water stress, and water productivity of teff (*Eragrostis tef*) *Agric. Water Manag.* **98** 775–83

Asmamaw D K 2015 A critical review of integrated river basin management in the upper Blue Nile river basin: the case of Ethiopia *Intl. J. River Basin Manag.* **13** 429–42

Assefa S, Biazin B, Muluneh A, Yimer F and Haileslassie A 2016 Rainwater harvesting for supplemental irrigation of onions in the southern drylands of Ethiopia *Agric. Water Manag.* **178** 325–34

Awulachew S B, Merrey D, van Koopen B and Kamara A 2010 Roles, constraints, and opportunities of small-scale irrigation and water harvesting in Ethiopian agricultural development: assessment of existing situation *Proc. of the ILRI Workshop (Colombo, Srilanka, 14–16 March 2010)* (IWMI, Addis Ababa, Ethiopia)

Awulachew S B, Yilma A D, Loulseged M, Loiskandl W, Ayana M and Alamirew T 2007 *Water Resources and Irrigation Development in Ethiopia* (Colombo, Sri Lanka: IWMI) p 66

Bekele S 2017 The response of tomato to deficit irrigation at Ambo, Ethiopia *Journal of Natural Sciences Research* **7** 48–52

Bekele S and Tilahun K 2007 Regulated deficit irrigation scheduling of onion in a semiarid region of Ethiopia *Agric. Water Manage.* **89** 148–52

Berihun B 2011 Effect of mulching and amount of water on the yield of tomato under drip irrigation *J. Horticulture and Forestry* **3** 200–6

Beyene A, Cornelis W, Verhoest Niko E C, Tilahun S, Alamirew T, Adgo E, Pue J D and Nyssen J 2018 Estimating the actual evapotranspiration and deep percolation in irrigated soils of a tropical floodplain, northwest Ethiopia *Agric. Water Manag.* **202** 42–56

Birhanu K and Tilahun K 2010 Fruit yield and quality of Drip-Irrigated tomato under deficit irrigation *Afr. J. Food, Agriculture, Nutrition, and Deve.* **10** 2139–51

Bouman B A M 2007 A conceptual framework for the improvement of crop water productivity at different spatial scales *Agric. Systems* **93** 43–60

Derib S D, Descheemaeker K, Haileslassie A and Amede T 2011 Irrigation water productivity as affected by water management in a small-scale irrigation scheme in The Blue Nile Basin, Ethiopia *Exp. Agric.* **47** 39–55

Dirirsa G, Woldemichael A and Hordofa T 2017 Effect of deficit irrigation at different growth stages on onion (*Allium Cepa* L.) production and water productivity at Melkassa, Central Rift Valley of Ethiopia *Acad. Res. J. Agri. Sci. Res.* **5** 358–65

Enchalew B, Gebre S L, Rabo M, Hindaye B and Kedir M 2016 Effect of deficit irrigation on water productivity of onion (Allium cepal.) under drip irrigation *Irrig. and Drain. Sys Eng.* **5** 172

Erkossa T, Awulachew S B and Aster D 2011b Soil fertility effect on water productivity of maize in the Upper Blue Nile basin, Ethiopia *Agricultural Sciences* **2** 238–47

Erkossa T, Menker M and Betrie G D 2011a Eff of bed width and planting date on water productivity of wheat grown on vertisols, in the Ethiopian highlands *Irriga. and Drain.* **60** 635–43

Ersel Y, Selin A, Talih G, Necdet D and Fuat S 2010 Effect of different water stress on the yield and yield components of second crop corn in semiarid climate *J. Food, Agric. and Environ.* **8** 415–21

Etissa E, Dechassa N, Alamirew T, Alemayehu Y and Desalegn L 2014 Growth and physiological response of tomato to various irrigation regimes and integrated nutrient management practices *African Journal of Agricultural Research* **9** 1484–94

Falkenmark M and Rockström J 2004 *Balancing Water for Humans and Nature: the New Approach in Ecohydrology.* (London, UK: Earthscan) p 247

FAO 2011 The state of the world's land and water resources for food and agriculture *Managing Systems at Risk.* (Rome, Italy: FAO and Earthscan)

Fereres E and Soriano M A 2007 Deficit irrigation for reducing agricultural water use *J. Experi. Botany* **58** 147–59

Furgassa Z S 2017 The effect of deficit irrigation on maize crop under conventional furrow irrigation in adami Tulu Central Rift Valley of Ethiopia *Applied Engineering* **1** 1–12

Gebreselassie Y, Ayana M and Tadele K 2015 Field experimentation-based simulation of yield response of maize crop to deficit irrigation using AquaCrop model, Arba Minch, Ethiopia *African Journal of Agricultural Research* **10** 269–80

Geerts S and Raes D 2009 Review: deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas *Agric. Water Manag.* **96** 1275–84

Geerts S, Raes D and Garcia M 2010 Using AquaCrop to derive deficit irrigation schedules *Agric. Water Manag.* **98** 213–6

Geerts S *et al* 2008a Introducing deficit irrigation to stabilize yields of quinoa (*Chenopodium quinoa* Willd.) *Eur. J. Agron.* **28** 427–36

Gelu G 2018 Evaluation of furrow irrigation systems on onion yield and water use efficiency in Melokoza Woreda, Southern Ethiopia . *Irrig. and Drain. Sys Eng.* **7** 211

Giordano M A, Turral H, Scheierling S M, Treguer D O and McCornick P G 2016 *Beyond 'More Crop per Drop': Evolving Thinking on Agricultural Water Productivity.* (Colombo, Sri Lanka: IWMI Research Report) Forthcoming (https://doi.org/10.5337/2017.202)

Habtewold M and Gelu G 2019 The response of tomato (*Lycopersicon Esculentum*), to deficit irrigation at Arbaminch Zuria Woreda in SNNPR, Ethiopia *IJESC* **9** 22583- 22586

Hagos F, Makombe G, Namara R E and Awulachew S B 2009 *Importance of Irrigated Agriculture to the Ethiopian Economy. Capturing the Direct Net Benefits of Irrigation.* (Colombo, Sri Lanka: IWMI Research Report 128) (https://doi.org/10.4314/ejdr.v32i1.68597)

Hassen J M, Wondimu T, Fikadu R, Kebede B, Niguse A, Elias and Hailu K 2019 Wheat response to water stress conditions at different growth stages in Amibara, Ethiopia *African Journal of Agricultural Research* **14** 1493–8

Heng L K, Hsiao T, Evett S, Howell T and Steduto P 2009 Validating the FAO AquaCrop model for irrigated and water deficient field maize *Agro. J.* **101** 488–98

Hilemichael T and Alamirew T 2017 Water Productivity of Teff under Semi-Arid Climates *Journal of Environment and Earth Science* **7** 116–23

Hordofa T 2006 Achievements and prospects of irrigation research for the central rift valley of Ethiopia *Proc. of the workshop on Achievements and Priorities in Ethiopia with particular reference to the Amhara Region (Bahir Dar, Ethiopia, 5–7 December 2005)* pp 66–76 Amhara Region Agricultural Research Institute and SWHISA Project (eds.), Irrigation water management

Hsiao T C, Steduto P and Fereres E 2007 A systematic and quantitative approach to improve water use efficiency in agriculture *Irriga. Sci.* **25** 209–31

Jemal K and Berhanu S 2020 Effect of water application methods in furrow irrigation along with different types of mulches on yield and water productivity of maize (Zea mays L) at Hawassa, Ethiopia *Journal of Natural Sciences Research* **10** 1–14

Kifle T 2018 Evaluation of tomato response to deficit irrigation at Humbo Woreda, Ethiopia *Intl. J. Research-Granthaalayah* **6** 57–68

Kirda C, Topcu S, Kaman H, Ulger A C, Yazici A, Cetin M and Derici M R 2005 Grain yield response and N-fertiliser recovery of maize under deficit irrigation *Field Crops Res.* **93** 132–41

Linker R, Ioslovich I, Sylaios G, Plauborg F and Battilani A 2016 Optimal model-based deficit irrigation scheduling using AquaCrop: a simulation study with cotton, potato, and tomato *Agric. Water Manag.* **163** 236–43

Mahamed M B, Sarobol E D, Hordofa T, Kaewrueng S and Verawudh J 2011 Effects of soil moisture depletion at different growth stages on yield and water use efficiency of bread wheat grown in semi-arid conditions in Ethiopia *Kasetsart J. Nat. Sci.* **45** 201–8

Mengist Y and Tilahun K 2009 Yield and water use efficiency of deficit-irrigated maize in a semi-arid region of Ethiopia *Afri. J. Food, Agric. Nutrition and Deve.* **9** 1635–51

Mengistie D and Kidane D 2016 Assessment of the impact of small-scale irrigation on household livelihood improvement at Gubalafto District, North Wollo, Ethiopia *Agriculture* **6** 1–22

Mengistu D K 2009 The influence of soil water deficit imposed during various developmental phases on the physiological processes of tef (*Eragrostis tef*) *Agriculture, Ecosystems, and Environment* **132** 283–9

Meskelu E, Woldemichael A and Hordofa T 2017 Effect of moisture stress on yield and water use efficiency of irrigated wheat (*Triticum aestivum L.*) at Melkassa, Ethiopia *Acad. Res. J. Agri. Sci. Res.* **5** 90–7

Meskelu E, Woldemichael A and Hordofa T 2018 Effect of moisture stress on yield and water use efficiency of irrigated maize *Book of Irrigation and Watershed Management* ed W Atlabachew *et al* (Addis Ababa Ethiopia: Ethiopian Institute of Agricultural Research) (2018) (https://doi.org/10.14662/ARJASR2016.055)

Mirzaei A, Naseri R and Soleimani R 2011 The response of different growth stages of wheat to moisture tension in a Semiarid Land *World Applied Sciences Journal* **12** 83–9

Molden D, Oweis T, Steduto P, Bindraban P, Hanjra A M and Kijne J 2010 Improving agricultural water productivity: between optimism and caution *Agric. Water Manag.* **97** 528–35

Moser S B, Feil B, Jampatong S and Stamp P 2006 Effect of pre-anthesis drought nitrogen fertilizer rate and variety on grain yield, yield components, and harvest index of tropical maize *Agric. Water Manage.* **81** 41–58

Mulu A and Alamirew T 2012 Deficit irrigation application using center pivot sprinkler irrigation for onion production *Intl. J. Basic and Applied Sciences* **1** 148–59

Oweis T and Hachum A 2012 *Supplemental Irrigation: a Highly Efficient Water-Use Practice* (Aleppo, Syria: ICARDA)

Patane C, Tringali S and Sortino O 2015 Effects of deficit irrigation on biomass, yield, water productivity, and fruit quality of processing tomato under semi-arid Mediterranean climate conditions *Sci. Hort.* **129** 590–6

Pereira L S, Cordery I and Iacovides I 2012 Improved indicators of water use performance and productivity for sustainable water conservation and saving *Agric. Water Manag.* **108** 39–51

Prosdocimi M, Jordán A, Tarolli P, Keesstra S, Novara A and Cerdà A 2016 The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards *Sci. of the Total Environ.* **547** 323–30

Rockström J, Karlberg L, Wani S P, Barron J, Hatibu N, Oweis T, Bruggeman A, Farahani J and Qiang Z 2010 Managing water in rain-fed agriculture: the need for a paradigm shift *Agric. Water Manag.* **97** 543–50

Rockström J, Lannerstad M and Falkenmark M 2007 Assessing the water challenge of a new green revolution in developing countries *Proc. Natl Acad. Sci. USA* **104** 6253–60

Rosin K G, Kaur R, Patel N, Rajput T B S and Kumar S 2017 Yield and irrigation water use efficiency of bottle gourd (*Lagenaria sicenaria L.*) in response to different irrigation methods and planting geometries *Int. J. Curr. Microbiol. App. Sci.* **6** 2475–81

Scheierling S M and Treguer D O 2016 Water productivity in agriculture: looking for water in the agricultural productivity and efficiency literature *Water Economics and Policy* **2** 2

Seid M M and Narayanan K 2015 Effect of deficit irrigation on maize under conventional, fixed, and alternate furrow irrigation systems at Melkassa, Ethiopia *Intl. J. Engi. Res. and Techn.* **4** 119–26

Shelemew Z, Hordofa T and Quraishi S 2019 The response of maize to deficit irrigation under three furrow irrigation systems in Adami Tulu Rift Valley, Central Ethiopia *International Research Journal of Multidisciplinary Studies* **5** 1–26

Steenbergen F V, Hailu A and Meta M 2004 Managing 'green water' or soil moisture management *Enabling Poor Rural People to Overcome Poverty in the Case Study in Burkina Faso* (Rome, Italy: IFAD)

Stone P J, Wilson D R, Reid J B and Gillespie R N 2001 Water deficit effects on sweet corn. Water use, radiation use efficiency growth, and yield *Aust. J. Agric. Res.* **52** 103–13

Tari A F 2016 The effects of different deficit irrigation strategies on yield, quality, and water-use efficiencies of wheat under semi-arid conditions *Agric. Water Manag.* **167** 1–10

Temesgen T, Ayana M and Bedadi B 2018 Evaluating the effects of deficit irrigation on yield and water productivity of furrow irrigated onion (Allium cepa L.) in Ambo, Western Ethiopia *Irriga and Drain Sys Eng.* **7** 1–6

Topcu S, C Kirda Y, Dasgan H, Kaman M, Cetin A, Yazici A and Bacon M A 2006 Yield response and N fertilizer recovery of tomato grown under deficit irrigation *Eur. J. Agron.* **26** 64–70

Tsegay A 2012 Improving crop production by field management strategies using crop water productivity modeling: a case study of tef (*eragrostis tef*) Trotter) production in Tigray, Ethiopia *PhD Thesis* KU Leuven, Belgium

Tsegay A, Vanuytrecht E, Abrha B, Deckers J, Gebrehiwot K and Raes D 2015 Sowing and irrigation strategies for improving rainfed tef (*Eragrostis tef* (Zucc.) Trotter) production in the water-scarce Tigray region, Ethiopia *Agric. Water Manag.* **150** 81–91

Yihun Y M 2015 Agricultural water productivity optimization for irrigated teff (Eragrostic teff) in a water-scarce semi-arid region of Ethiopia *PhD Thesis* UNESCO-IHE Institute for Water Education, The Netherlands

Yihun Y M, Haile A M, Schultz B and Erkossa T 2013 Crop water productivity of irrigated teff in a water stressed region *Water Resour. Manag.* **27** 3115–25

Zwart S J and Bastiaanssen W G M 2004 Review of measured crop water productivity values for irrigated wheat, rice, cotton, and maize *Agric. Water Manag.* **69** 115–33