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Estimating Evapotranspiration of Maize under Different Management Practices in a Semiarid Tropical Area Using the Soil Water Balance Method

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Abstract

Smallholder farmers in semiarid areas face low and erratic rainfall and need field management practices that conserve water in the root zone. This work evaluated the effect of mulching and DD (deep tillage) practices as a way to conserve soil moisture and thus improve water availability and maize crop yield in this water-scarce environment. The field experiment was carried out in which the soil moisture content (SMC) was monitored and the other water balance components were measured to quantify the crop ET with the soil water balance (SWB) method. The components of the SWB (rainfall, supplemental irrigation, runoff, deep percolation and change of soil moisture content) were measured for three consecutive seasons of 2018-2019, i.e. two long rain seasons (Masika 2018 and 2019) and one short-rains season (Vuli 2018). The estimation of the deep percolation (DP) involved calculating water fluxes from hydraulic properties measured in the laboratory and from hydraulic gradients measured with tensiometers in the field plots. Treatments significantly affected ET ($p < 0.05$) during the Vuli 2018 season. The estimated ET was highest in FC plots, medium in DD, and FCM recorded the lowest ET value. The significant difference in ET was between FCM and other treatments. Relative to a control treatment (farmers' cultivation, FC), mulching (FCM) reduced evapotranspiration by 14% and 18% during more water-stressed seasons of Vuli 2018 and Masika 2019. The ET reduction among the treatments was in line with the reduction in soil evaporation, as reflected in the results (of the other article of the same work). The crop transpiration was observed higher, which was consistent with the higher canopy cover observations for the two treatments relative to the FC treatment. Also, while the mulch practice did not affect ET during the first and less water-stressed season of Masika 2018, DD reduced it by 9% and showed no effect during other seasons.

Keywords

Evapotranspiration, Deep Percolation, Soil Hydraulic Properties, Makanya Catchment, Semi-Arid

1. Introduction

Evapotranspiration and rainfall are the key components of the global water cycle (Miralles et al., 2011), although they are not uniformly distributed around the globe. Evapotranspiration accounts for about 60% of the global terrestrial precipitation (Anderson et al., 2017; Haddeland et al., 2011). This makes it a major component of the water cycle from the earth to the atmosphere (Zhang et al., 2014).

Arid or semiarid areas receive little rainfall and are mostly found in hot regions of the tropics, with high atmospheric evaporative demand thus, making agriculture in these areas prone to drought. About 80% of global agriculture is rainfed (Rockström & Barron, 2007). This means that the globe relies on rainfall for food production. Although agriculture is crucial for food security and economic reasons (especially for developing countries), there is a challenge of poor crop production in arid and semiarid areas. Rainfed crops in these areas suffer from drought stress (Li et al., 2015), leading to low crop productivity.

The study area of the Makanya catchment in northern Tanzania is semiarid, with annual rainfall ranging between 500 and 600 mm/year. The rainfall in the area is lower than the maize crop water requirement and is distributed with high temporal variations that lead to dry spells within rainy seasons (Fischer et al., 2013). The erratic rainfall distribution with few intensive events and dry spells results in low crop production in the area. A big part of the rainwater received in fields of the semiarid regions is reported to be lost through non-productive flows, mainly as soil evaporation (Rockström et al., 2003). Soil evaporation (a component of ET) is influenced by climatic factors, soil characteristics and land management practices. It is a major source of water loss from agricultural fields in hot drylands (Enfors et al., 2011). Low and unreliable rainfall and high evaporative water loss from the soil surface lead to low crop yields and sometimes crop failure in these areas.

It is therefore vital to assess ET for developing more efficient and sustainable water management techniques in water-scarce areas (Watanabe et al., 2004). ET quantification is also needed to validate hydrological models (Miralles et al., 2011) to accurately simulate water fluxes and crop productivity.

Various methods are used to quantify ET in different regions of the globe. For example, Li et al. (2008) estimated a seasonal ET in a maize field with plastic mulch from a temperate arid climate region. This study estimated ET using the eddy covariance (EC) method and reported the average daily maize crop ET of 4.96 mm, an indication of a high water usage through ET that would lead to its deficit during the crop growth. The study of Watanabe et al. (2004) for a tropical semiarid region with an annual rainfall of 1200 mm estimated ET from different crop fields and reports an average daily ET of 7 mm/day in a maize field that exceeded those of other crops. This study estimated the ET using the Bowen ratio energy balance (BREB) method and the seasonal ET (for 4 months maturity duration of maize) was about 840 mm. The estimated ET amounted to 70% of the recorded seasonal rainfall, which would lead to a water deficit for maize crops in the area depending on the proportion of ET that the plant used for growth and the one that got lost through soil evaporation. Another study by Li et al. (2018) in the warm, semi-humid climate region with an annual rainfall of 660 mm investigated different mulching strategies on soil water storage, ET, yield and water use efficiency WUE of maize during the two growing seasons. The studied mulch types were plastics, sand gravel and crop residues, and the ET was estimated using lysimeters. The experiment was conducted in containers, and all mulch types were reported to improve water storage, crop yield, and water use efficiency, with the highest increase observed in crop residue mulches.

ET has also been estimated using empirical models (that utilize meteorological data) and remote sensing techniques with ground or vegetation satellite images. Li et al. (2016) evaluated six empirical models for estimating the potential (PET) and actual (ETa) evapotranspiration of maize in different climates, including an arid climate with a very low annual rainfall of 164 mm and supplemental irrigation treatments. The actual ET data were measured directly from the field using the EC method. The empirical models that were tested are; FAO Blaney-Criddle (BC), Hargreaves, Priestley-Taylor (PT), Dalton, Penman (PE) and Shuttleworth (SW). The study reported PE, PT and SW with good performance based on the coefficient of determination and this was related to the fact that these three models use more meteorological variables than the rest. On the other hand, the study argues that the accuracy of the PET models in estimating actual crop ET depends on the accurate estimation of the crop factor (Kc).

Though both BREB and EC (Baldocchi et al., 2001; Wilson et al., 2001) methods are commonly used for estimating actual crop evapotranspiration on a large spatial scale, they are expensive for low-income researchers and are rarely used in developing countries. Another challenge for BREB and EC methods is the inability to compare different agricultural management practices. This is due to their large and variable footprint that precludes their use in field trials with treatments replicated in field plots. Finally, although the EC is considered a standard method that can capture the actual ET even over a short period, it needs several corrections before it can be used.

However, all of these mentioned techniques can not be used in small fields where treatments need to be compared experimentally. This makes the ET data scarce in the dry areas of developing countries where there are only a few options for ET estimation, yet this is highly needed for water resource management.

One of the extensively used and considered less costly methods to estimate ET is a lysimeter (Anapalli et al., 2016; Pütz et al., 2016; Gebler et al., 2015) that directly measures all components of the water balance except for ET. ET is then calculated as the only unknown variable in a water balance equation based on the principle of conservation of mass for the soil volume contained in the lysimeter. The method is costly if the lysimeters are constructed sufficiently large and contain undisturbed soil monoliths (which should have proper experiments), as was the case for the Pütz et al. (2016) study. It is seldom used to evaluate the effects of field management practices on crop ET because the limited surface area of lysimeters precludes the proper implementation of these practices.

A traditional and direct field ET measurement method is the soil water balance method (SWB). The SWB method is similar to the lysimeter method, except that it measures all fluxes through measurements in field plots, not from lysimeters. It can therefore be used to assess the effect of management practices on field water dynamics. The method is simple and accounts for all fluxes influencing root zone water content (Wilson et al., 2001). The water fluxes include both incoming ones such as rainfall and supplementary irrigation (SI) and outgoing fluxes such as surface runoff (RO) and deep percolation (DP). The deep percolation losses depend on soil hydraulic properties (Ben-Asher & Ayars, 1990; Pereira et al., 2009) and are the hardest component to determine and are often neglected in similar studies (Chanasyk et al., 2006; Singh et al., 2017). The ET estimation using this method is similar to the one of the lysimeter method.

There are no studies on ET quantification under management practices in the current study area. Therefore, the current study is the first to assess management practices' effect on water conservation by reducing Es, the unproductive component of the ET.

The studied agricultural management practices in the study area include Fanya juu (soil bunding), trenching, borders cultivation, use of ndiva (manmade micro-dams to collect water from the upland of the catchment for supplemental irrigation), conservation tillage and mulching (Makurira et al., 2011; Enfors et al., 2011). These practices are meant to reduce runoff, enhance soil water storage, combat the effects of dry spells in the seasons and improve crop productivity. However, although they are of much importance, especially supplemental irrigation, not all techniques are proven to realize all the aims. For example, the collected water in micro dams is expected to irrigate the farms on lower land through earthen furrows or channels by gravitational movement. However, the amount of water in the dams depends on the rainfall, which is, in most cases, not enough for all farms in the area. In addition, the surface type of irrigation practised in the area is field flooding which may cause waterlogging (Joshi, 1987).

Waterlogging is not a good feature of the land (FAO, 2001) as it may destroy the soil structure by sealing, reducing infiltration capacity in the field and may accelerate soil evaporation. Fanya juu trenching practices were reported to concentrate more water (≥50%) beyond the root zone, where it is not easily accessible by plants (Makurira et al., 2011). Enfors et al. (2011) tested the management practices of ripping, mulching and conservational tillage for in situ water harvesting and its conservation. They reported a 41% crop yield increase due to the combined effect of all the treatments. However, the same study reported that there was no or little effect on soil physical and hydraulic properties, but the effect on ET or Es was not quantified. The water consumption of agricultural management practices that reduce water loss through soil evaporation (as a component of ET) during crop growth or those that improve rainfall water infiltration and conservation into deeper depths have not been assessed in the area.

The study aimed to evaluate the effect of mulching and DD (deep tillage) practices as a way to improve yield by improving water availability to maize in this water-scarce environment. Thus, the study set up a field experiment in which the soil moisture content (SMC) was monitored and the other water balance components were measured to quantify the crop ET with the soil water balance method. The study location was chosen to represent the semiarid areas where poor crop yields challenge smallholder rainfed crop production due to little and erratic rainfall.

2. Materials and Methods

2.1. Experimental Site Description

The study area is located in the Bangalala village, one of the five villages of the Makanya catchment, in the Same District, Kilimanjaro region in the North-East of Tanzania. The village is in the midland; other villages are Vudee in the upland and Makanya in the lowland parts of the catchment.

The climate of the catchment is tropical, with slight variation within the catchment due to considerable differences in altitude and terrain. The average maximum temperature ranges from 26˚C to 32˚C (Mutiro et al., 2006). The rainfall regime within the catchment is influenced by local relief. Some parts of the catchment area are located in the rainfall shadow of the Pare mountain ranges to the East (on the dry side) from the rain-producing wind in the West. There are two rainy seasons experienced in this catchment. The long rain season (Masika) occurs between March and May, and the short rains (Vuli) are experienced between October and December. The Makanya catchment experiences low annual rainfall with an average of <400 mm/year in the lowland relief, between 500 to 600 mm/year at midland relief, and the wettest highland areas receive up to 800 mm/year (Mul et al., 2011). This makes the catchment with an average annual rainfall of around 600 mm year^{-1} (Mul et al., 2006) with few exceptional years that exceed 800 mm as it is observed from the 23 years of historical rainfall data from the Same weather station (**Figure 1**). As a result, the total monthly ET exceeds rainfall throughout the year (Figure 1).

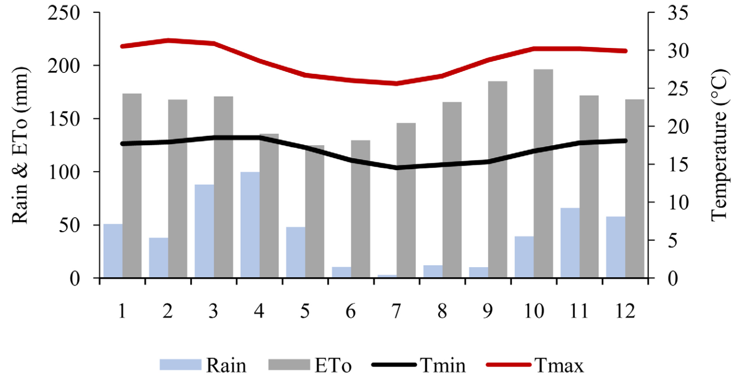

Figure 1. Mean monthly rainfall, ETo, and maximum and minimum air temperatures (red and black solid lines) for the Same station (4˚08'S, 37˚73'E; 886 masl) near Makanya catchment.

Table 1. Classification of the soil of the study area according to the World Reference Base (WRB).

Definition of Ferralsols - Having a ferric horizon at some depth between 25 and 200 cm from the soil surface, and - Lacking a nitic horizon within 100 cm from the soil surface, and - Lacking an argic horizon with 10 per cent or more water-dispersible clay within 30 cm from its upper boundary unless the soil material has geric properties or contains more than 1.4 per cent organic carbon		
Connotation	Parent materials	Profile development
Red and yellow tropical soils with a high content of sesquioxides from L. Ferrum-iron.	Strongly weathered materials, on old strong geomorphic surfaces, more in weathering material from the basic rock than in siliceous material	ABC profiles. Deep and intensive weathering has resulted in a high concentration of residual, resistant primary minerals alongside sesquioxides and well-crystallized kaolinite. The mineralogy and pH explain the yellowish (goethite) or reddish (hematite) soil colours.
Geological description of the site and parent material		
Age	Lithology	Other information
Proterozoic	Precambria/Oregenic Belt	Parent rocks
	The System (Usagaran) comprises sedimentary, volcanic rocks and gneisses, amphibolites and lenses of granulites	Highly metamorphosed

Continued

Hydro-physical properties of the soil of the study area						
Depth (cm)	Clay (%)	Sand (%)	ρ_b (g/m^3)	θ_{PWP} (%)	θ_{FC} (%)	θ_{SAT} (%)
0 - 30	41.1	49.2	1.44	11.9	22.5	44.0
30 - 60	40.1	52.2	1.35	16.1	24.0	43.6
60 - 90	40.1	55.2	1.35	15.5	26.6	45.4
90 - 120	32.1	59.2	1.37	15.4	26.2	45.3

Due to the hot nature of the tropics, which leads to high radiations and evaporative demands, the little rainfall that falls on cultivated lands of semiarid areas gets lost through evapotranspiration (ET). As a result, the region experiences food insecurity due to drought caused by low rainfall, which is often accompanied by dry spells during crop growing seasons and thus leads to poor crop yields. It is aggravated by water loss from crop fields as soil evaporation due to the high evaporative demand of the atmosphere. In addition to the fact that the area's climate is not conducive to crop production, the future projections still indicate its volatility with an expected upsurge in temperature, unpredictable rainfall (decrease and increase depending on location), and prolonged dry spells (URT, 2007). The mean annual temperature is projected to increase between 2˚C and 4˚C, while the shift in rainfall change remains uncertain (Luhunga et al., 2018). This climate volatility is projected to impact crop production in low-income and drought-prone countries that rely on rainfed crop production, such as Tanzania (Ahmed et al., 2011). Rowhani et al. (2011) argue that the projected temperature increase and the change in total seasonal precipitation in Tanzania will reduce the average yield of major cereals (maize, sorghum, and rice) by 2050. The study reports that the increase in temperature is projected to reduce yields of maize by 13%, sorghum by 8.8%, and rice by 7.6%, while the expected intraseasonal rainfall variations are projected to decrease the same crop yields by 2.4%, 7.2%, and 7.6% respectively.

The soil properties (physical, chemical, and mineralogical properties) and classification for the study area soils are listed in **Table 1**.

2.2. Experimental Treatments and Design

Measurements of the soil water balance components for estimating crop evapotranspiration were carried out over three growing seasons of Masika and Vuli in 2018 and Masika in 2019. The first season (Masika 2018) was rainfed, and it started in mid-March and ended in June 2018. The second season (Vuli 2018) commenced in mid-October 20018 and ended in January 2019, and it was supplemented with irrigation water. Finally, the last study season of Masika 2019 started on the 6th of March and ended in June, and it was also supplemented with irrigation water from manmade micro-dams, Ndivas.

During the first season, the experiment was established with three field management practices, namely farmers' cultivation (FC), farmers' cultivation with mulching (FCM) and double digging (DD). FC means land preparation was done by digging with a normal hand hoe on a shallow depth (say 0 - 6 cm from the surface) to remove any unwanted plants and without turning the soil as done by farmers, and therefore served as a control. FCM was done as in FC but by spreading 11.4 t/ha maize stovers over about 80% of the ground on both sides of the crop rows, leaving the planting line (about 20% of the crop row area) uncovered. DD is first done as in FC but additionally involves making a planting row by digging twice deep (to about 50 cm from the surface) using a small (25 cm long and 10 cm wide) hand hoe. The hand hoe loosens any compacted soil layer for easy incorporation of organic manure and enhances redistribution of water deeper into the soil profile. The manure was first added to the planting hole, and seeds were sown and covered with a layer of soil. The hypothesis on the DD treatment was that it would improve redistribution and deeper water infiltration, similar to the deep tillage effect as reported by Campbell and Akhtar (1990), thus increasing its availability at the root zone as also discussed in Schneider et al. (2017). As a result, evaporation is reduced at the soil surface compared to a minimum-till practice (FC) with water redistribution ability; a similar finding on the effect of tillage on Es is reported in Sillon et al. (2003). But the risk is that with a long prolonged period of heavy rains, the more intensely tilled soil of the DD treatment may become compacted, and its infiltration capacity could be reduced. Treatments were replicated three times and arranged in a randomized complete block design. The field plot size was 10 m by 7 m, and a spacing of 1.5 m was left between the blocks and 1 m between plots within a block as pathways in the experimental plot (**Figure 2**). The experimental layout and treatment plots were maintained through the next two seasons, the end of the study.

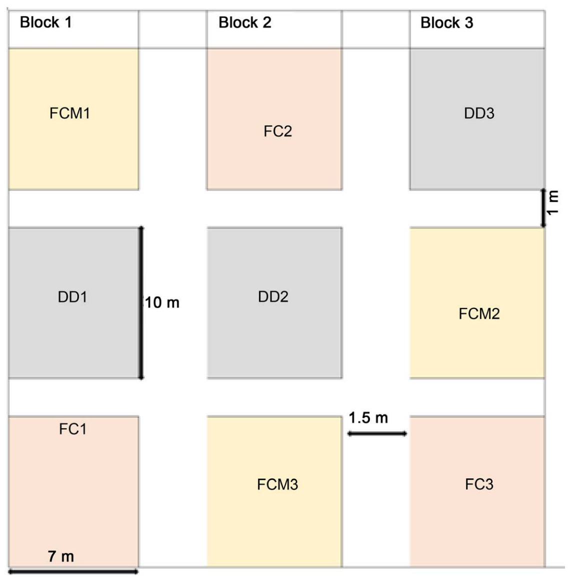

Figure 2. Experimental layout: treatments FC = farmers cultivation; DD = double digging; FCM = farmers cultivation with mulch replicated three times in a randomized complete block design.

The soil water balance components, including rainfall, runoff, deep percolation, rootzone water storage and supplemental irrigation for non-rainfed seasons, were measured during the three consecutive seasons of Masika 2018, Vuli 2018 and Masika 2019. The effect of each agricultural management practice on crop evapotranspiration is subsequently evaluated herein.

2.3. Rootzone Water Storage Measurements

The soil water content in the root zone (0 - 120 cm) was determined by taking auger samples in each of the nine plots and drying them in the oven at 105˚C for 48 hours. The auger samples were taken every three weeks starting from the 24th of March 2018 with a 0.03 m diameter gouge auger. The samples were taken at the depths of 0 - 30 cm, 30 - 60 cm, 60 - 90 cm and 90 - 120 cm at five points per plot to obtain a composite sample per plot and depth. The gravimetric soil moisture content and bulk density were used to determine the volumetric water content, Equations (1) & (2) as described in Hillel (1980).

The gravimetric water content (θ_g) is expressed as g/g:

$$\theta_g = \frac{m_1 - m_2}{m_2 - m_c} = \frac{m_w}{m_s} \tag{1}$$

where: m_1—a mass of wet sample (g); m_2—the mass of oven-dried sample (g); m_s—the mass of soil (g); m_c—the mass of container (g); m_w—the mass of water (g).

The relationship between volumetric and gravimetric water content:

$$\theta_v = \theta_g \frac{\rho_b}{\rho_w} \tag{2}$$

where: θ_v—volumetric water content (cm^3/cm^3); θ_g—gravimetric water content (g/g); ρ_w—density of water (≈g/cm^3); ρ_b (bulk density)—m_s (g)/total volume of soil sample (cm^3).

The equivalent water depths, D_e (mm), stored in the root zone of a 4-layered 120 cm soil profile was determined as a summation of the product of volumetric water content and the equivalent thickness of each soil layer from the surface to the root zone as:

$$D_e = \sum_{i=1}^{n} \theta_i D_i \tag{3}$$

where θ_i is the volumetric water content (in cm^3/cm^3) of soil layer i, and D_i is the thickness (mm) of that soil layer i in the profile. Then, the difference between the equivalent water depths of two dates was used to calculate the change in the root zone water storage ΔWs_r (mm) of the 120 cm profile as follows;

$$\Delta Ws_r = \left[D_{e_{t_2}} - D_{e_{t_1}} \right]_0^r \tag{4}$$

where ΔWs_r is the change in the soil water storage, $D_{e_{t_1}}$ and $D_{e_{t_2}}$ are the equivalent water depths of the soil from the surface (0) to the bottom boundary of the root zone (r) (120 cm) between two successive measurements (dates).

2.4. Soil Matric Potential Measurements

The hydraulic gradient at the bottom of the root zone was determined from pressure head readings of T4e pressure transducer tensiometers from Meter Group, Inc. USA. These were installed with the tensiometer cup at 90, 120 and 150 cm depths in each plot. Each of the tensiometers was installed at an angle (α) of 65˚ from the ground. They were installed in such a way that after installation, the middle of the cups was installed at 90, 120, and 150 cm depths in the middle of each plot, and aligned along one vertical line, so gradients could be measured. Using a 3 cm diameter auger, a drilling depth (X) slanted from the ground was determined based on Pythagoras theory as X = installation depth/cos α for each of the tensiometers. The drilling depth was also marked on the tensiometer shaft to achieve the desired measurement depth. The reference or starting points for each plot were marked approximately in the middle of the plot. An angle iron[1] (an iron with the desired installation angle of 65˚ from the ground) was placed at different drilling points, i.e. 42, 56 and 70 cm, for drilling tensiometer installation holes for depths of 90, 120 and 150 cm. Distances (Y) of the installation points from the reference point were determined based on the same theory (Y = installation depth * tan α). This was to determine drilling depths and allow tensiometers to attain desired installation depths at one vertical line in a soil profile but in a different direction to avoid tensiometers covering each other and so to avoid the risk of damage during measurements. After installation, the installation angles to the horizontal surface and the tensiometers' depths in the soil profile were re-recorded. This was done to check and ensure the intended installation depths were maintained or with only a slight diversion. The actual elevations or depths (91, 121 and 151 cm for FCM, 90, 121 and 153 cm for DD and 90, 119 and 151 cm for FC) were very close to the intended ones (90, 120 and 150 cm) were used in the gradients calculations. Thermal insulation tubes made of insulation foam were used to protect the tensiometers' heads against excessive heating by the sun. Whenever there was any misbehaviour in readings due to air bubbles in the tubes, tensiometers were refilled to remove the air bubbles. The tensiometers were refilled when the soil got too dry (more than - 750 hPa). The tensiometers were connected to INFIELD 7 readout unit Meter Group for taking pressure readings. The readings were taken every second day between 9:00-11:00 am.

2.5. Rainfall and Other Weather Data

Rainfall was measured using a manual rain gauge mounted on a pole at the height of 1.5 m above the land surface within the experimental site. The daily recordings in mm were taken at 9:00 am. In addition, solar radiation, air temperature (minimum and maximum), humidity and wind speed were collected from an automatic weather station located about 1.5 km from the experimental site and used for calculating reference evapotranspiration according to FAO 56 (Allen et al., 1998).

2.6. Supplemental Irrigation (SI)

During the Vuli season (October 2018-January 2019) and Masika (March-June

[1]A metal iron fabricated with a desired installation angle.

2019) season, there were supplemental irrigations. The irrigation in the area is done by gravitational force, where water flows downstream to the fields through earth furrows. In the current study, there was no specific irrigation schedule, and crop water requirement was not considered at each time due to limited water in the dam and the high number of farms in need of the resource. Irrigation was done only during critical crop growth stages in the seasons. Whenever supplementary irrigation (SI) was given, all plots received about the same amount (when expressed in mm) of water. This was achieved by maintaining a constant flow rate (and monitoring that rate), directing all water into one plot at a time, and using the same irrigation duration in each equal-sized plot. The FCM plots received slightly more water (by 5% more) during both Vuli 2018 and Masika 2019 seasons because of the delay in water distribution over the plots due to resistance imposed by mulches. The total volumes of SI water that were determined by summing up actual volumes on different irrigation events for each treatment and season are presented in **Table 2**. The average irrigation volume per treatment during the Vuli season was 38 mm for FCM, 35 mm for DD and35 mm for FC. During the Masika 2019 season the amount was 31 mm for FCM, 29 mm for DD and 29 mm for FC. This was achieved by letting the water enter each plot, one plot at a time, monitoring the inflow's discharge with a V-notch weir having an angle of 90˚, and cutting off the inflow when there was enough well-distributed wetness within the plot. The head, which is considered the water depth upstream of the V-notch, was recorded after installing the notch at the entry of the plot and the start and the end of the water application in each plot. The discharge into the plots was kept constant by a control valve at the water source. The discharge was calculated from the measured head (h) following the Kindsvater-Shen equation as detailed in USBR (2001) and Shen (1981):

$$Q = 2.363C * \tan\left(\frac{\theta}{2}\right)(h+k)^{\frac{5}{2}} \quad (5)$$

where Q is the discharge (m^3/s) into the experimental plots, θ is the notch angle in degrees, C is the discharge coefficient, h is the measuring head in m, and k is the head correction factor in m, and the discharge was converted from ft^3/s to m^3/s by a factor of 2.363.

2.7. Runoff Collection

The surface runoff (RO) was measured using a constructed and plastic tarpaulin-lined ditch at the lower border of each of the nine plots. The ditches had a trapezoidal cross-section (25 cm bottom width, 60 cm depth) and a length equal to the plot width. A 15-cm high earth ridge around each plot and ditch prevented that water from outside from entering the plot or the runoff-collection ditch. The water collected in the rain gauge was recorded every morning at 9:00. If the rain had occurred, water in the runoff ditches also was quantified at the same time. The runoff was calculated following a 3-step procedure:

1) The volume of rainfall that directly fell into each ditch was calculated as:

$$V_c = P \times A_1 \tag{6}$$

where is the calculated volume of rainfall that fell directly into the ditch (L); P is rainfall recorded in the standard rain gauge (mm); A_1 is the catchment area of a tarpaulin after installation (m^2).

2) The water from the ditches in each plot was scooped out, and V_m, the volume of water, was measured with a large graduated cylindrical bucket.

3) The runoff per plot was calculated as:

$$R = \left(V_m - V_c\right) / A \tag{7}$$

where R is the surface runoff (mm); is the volume of water collected from the ditch (L); is the estimated volume of rainfall that fell directly into the ditch (L); A is the plot area (m^2).

2.8. Determination of the Soil Hydraulic Properties at the Bottom of the Root Zone with the Multi-Step Outflow Method

The soil hydraulic properties at the bottom of the root zone (120 cm) were determined in the laboratory using the Multi-step Outflow method (van Dam et al., 1994). The multi-step outflow experiment measures the cumulative outflow from a soil core against time. The soil cores used to determine soil hydraulic properties and the unsaturated conductivity (Kh) were considered representative of the field soil profile. The representativeness was considered since the profile consisted of one thick layer from the surface to 90 cm with one textural class and a second thin layer (from 90 to 120 cm) with a slightly different texture, as described in **Table 1**. However, it is impossible to capture field variability, connectivity and continuity (large continuous pores) and other factors that determine hydraulic conductivity from the soil sample cores. The soil cores are subjected to pneumatic pressure increments at the top with a saturated ceramic plate at the bottom. The experiment was conducted on four undisturbed soil sample rings (5.7 cm high, diameter 5 cm and 100 cm^3 volume). The samples were placed in Tempe pressure cells on top of (7 mm thick, $K_s \approx 0.01$ cm/hr) ceramic plates. The pressure was increased in steps to 60, 180, 260, 360 and 1000 cm values. During the experiment, simultaneous recording of the pressure increments and the cumulative outflow versus time was done. The outflow was fitted in HYDRUS 1D (**Figure 3**) through an inverse solution modelling technique and used to estimate the soil hydraulic properties (Durner & Iden, 2011; Hopmans et al., 2018; Crescimanno & Iovino, 1995; van Dam et al., 1994; Eching et al., 1994). The water retention characteristics (WRC) were also measured in the laboratory to improve the parameter estimation technique, and the observed matric heads (h) from this experiment were used in the soil hydraulic parameter estimation procedures. The WRC was determined in the laboratory on four undisturbed soil samples of 100 cm^3 taken at 120 cm depth using the sandbox and pressure chambers. The retention curve measured on the sandbox was for pF values of 0.00, 0.50, 1.00, and 1.50. In the low-pressure chambers, the measured retention curve was for pF values of 2.51 (field capacity) and 2.80. The pF values of 3.4 and pF 4.18 (permanent wilting point) were determined in the high-pressure chambers. The soil hydraulic properties from inverse solution were used to determine soil hydraulic properties (n, m, η, θ_s, θ_r, l, α, K_s) and finally, the unsaturated hydraulic conductivity, $K(h)$ by the van Genuchten-Mualem relationship (van Genuchten, 1980):

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{8}$$

where (cm/day) is the unsaturated hydraulic conductivity as a function of the soil water potential. K_s (cm/day) is the saturated hydraulic conductivity; l is the tortuosity (fitting parameter-dimensionless, taken as 0.5); and is the effective saturation defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{9}$$

with $$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{10}$$

The unknown soil hydraulic properties which were estimated during inverse modelling were: residual (θ_r) and saturated (θ_s) soil water contents, saturated hydraulic conductivity (K_s) and the shape parameters in the soil water retention function (α and n).

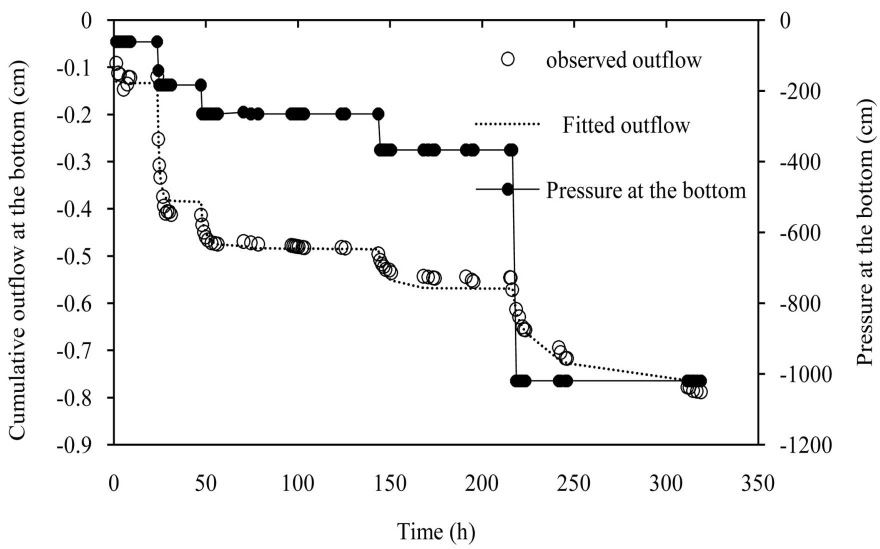

Figure 3. Observed (circles) and simulated (dash lines) cumulative outflow vs time used during the multi-step outflow experiment. The dark black line with markers is the pressure head at the bottom of the ceramic plate on which the soil sample is placed.

2.9. Estimation of Deep Percolation (DP) at the Bottom of the Root Zone

Deep percolation losses (DP) at the bottom of the root zone (120 cm) for each plot were calculated with the Darcy-Buckingham equation as explained in Angulo-Jaramillo et al. (2016); Saito et al. (2006) as follows:

$$J_w = -K(h)\left(\frac{\mathrm{d}h}{\mathrm{d}z}+1\right) \tag{11}$$

where J_w is the vertical water flux (cm/day); h is the soil water potential heads (cm); z is the vertical spatial coordinate (cm, positive upward); K is the unsaturated hydraulic conductivity (cm/day); ($\mathrm{d}h/\mathrm{d}z$) is the pressure head gradient. A negative J_w means the presence of a DP (DP = $-J_w$), and a positive J_w means an upward water flow or capillary rise. The tensiometer readings (the soil moisture tensions) at 90, 120 and 150 cm depths from the profile were used to determine the pressure head gradient at the root zone. The maize crop rootzone was identified at 120 cm; therefore, the gradient ($\mathrm{d}h/\mathrm{d}z$) was determined from water potential heads at 90 and 150 cm depths. The hydraulic conductivity $K(h)$ was derived from the relationship obtained with the Multi-step Outflow method and the tensiometer reading at 120 cm. Since the tensiometer readings were taken every second day, the deep percolation (DP) on days without measurement was obtained by linear interpolation between two successive reading days.

2.10. Closing the Soil Water Balance (SWB)

The soil water balance method is used to estimate crop evapotranspiration (ETc) based on mass conservation principles in the root zone (Li et al., 2008). The root zone in this study was considered to extend to a depth of 120 cm in the soil profile based on the observed root distribution of the maize. Calculations of the ET based on the SWB components for the root zone were done as follows;

$$\mathrm{ET} = \mathrm{P} + \mathrm{SI} - \mathrm{DP} - \mathrm{RO} - \Delta \mathrm{Ws_r} \tag{12}$$

where P is rainfall (mm), SI is supplemental irrigation (mm) (done in two seasons out of the three); RO is surface runoff (mm); DP is deep percolation or drainage beyond the root zone (mm); ET is the actual evapotranspiration, and ΔWs_r is the increase in soil water storage (mm) at the rootzone between two successive moisture determinations (so ΔWsr. is negative when it is a decrease). The ET per plot was deduced from other components of the SWB and was expressed in units of mm/day. The ET, P, SI, DP and RO are the totals over the period between two successive soil moisture determinations. The SI component was not considered in the equation for the first season, which was complete rainfed, without irrigation water.

2.11. Statistical Analysis

The experimental data for each SWB component were analyzed using JMP Pro 14 with a mixed model personality. The date effect on results was further considered in the repeated measures analysis. Treatment differences in the components of the SWB were established using analysis of variance, and when significantly different, treatment mean differences were established using Tukey HSD all pairwise multiple comparisons at 95% confidence levels.

3. Results and Discussion

3.1. Rainfall and Supplemental Irrigation

The rainfall recording for the experimental data during the long rainfall season of Masika 2018 started on the planting date, the 15th of March. The recorded total rainfall over the crop growth season (planting to harvesting) was 165.3 mm, the lowest as compared to rainfall in other seasons. In this season, before planting, the rainfall had already thoroughly wetted the soil profile (212 mm rain before planting). From planting up to mid-May 2018, rainfall was (just) sufficient to meet evaporative demand; after that, it decreased too much and resulted in a seasonal total of 165.3 mm that could not compensate for an ETo of 324.7 mm (**Figure 4**). Although rainfall came in small volumes (<1 mm on some days close to the end of the season), it did not stop until 90 days after planting, when the maize was close to maturity. The crop matured with the residual soil moisture with only a little evaporation loss favoured by the season's cool weather. No supplemental irrigation (SI) was applied in this season. The rainfall during the two later seasons came in normal intensities, but few periods had long dry spells between the rain events that subjected crops to water stress. The rainfall recording in Vuli 2018 season started on the 15th of October, which was a planting date. A few days after one first light rainfall event of less than 2 mm, the second event came after a week. The total recorded rainfall was 239 mm during Vuli 2018 crop growth season. Although rainfall during Vuli 2018 season was higher than the rainfall in the previous season (**Figure 4**), it was less well distributed. The rainfall in the Masika 2019 season came one month later than the usual expected time.

The recording commenced on planting day after a few rainfall events, and the total rainfall during this season was recorded at 177 mm. The little rains with dry spells during these two seasons that occurred on dry and hot soils (the hottest month before Vuli is October) with high evaporative demand led to low soil moisture, and it had to be supplemented with irrigation to sustain the crops. The supplemental irrigation was done in four events in Vuli 2018 and three times in Masika 2019 during critical crop growth stages in the seasons. Irrigation scheduling for each season was determined by water availability in the source reservoirs. The average volume of SI water (for all treatments) for the Vuli 2018 and Masika 2019 seasons is presented in **Table 2**. The SI and seasonal rainfall total 374 mm for the Vuli 2018 and 263 mm for the Masika 2019 season. However, this falls short of the evaporative demand of 457.9 mm recorded during the Vuli 2018 season and 392.2 mm during the Masika 2019 season (**Figure 4** and **Table 3**). The irrigation water during the seasons depended much on its availability instead of the requirement of the crops in terms of volume and timing. The reason for this was that water availability in the micro dam depended on the amount of rainfall that comes in the upland of the catchment and the number and sizes of farms that needed water during the same season. Rainfall in the Vuli 2018 season was high and enabled the collection of more irrigation water in the dams than for the Masika 2019 season.

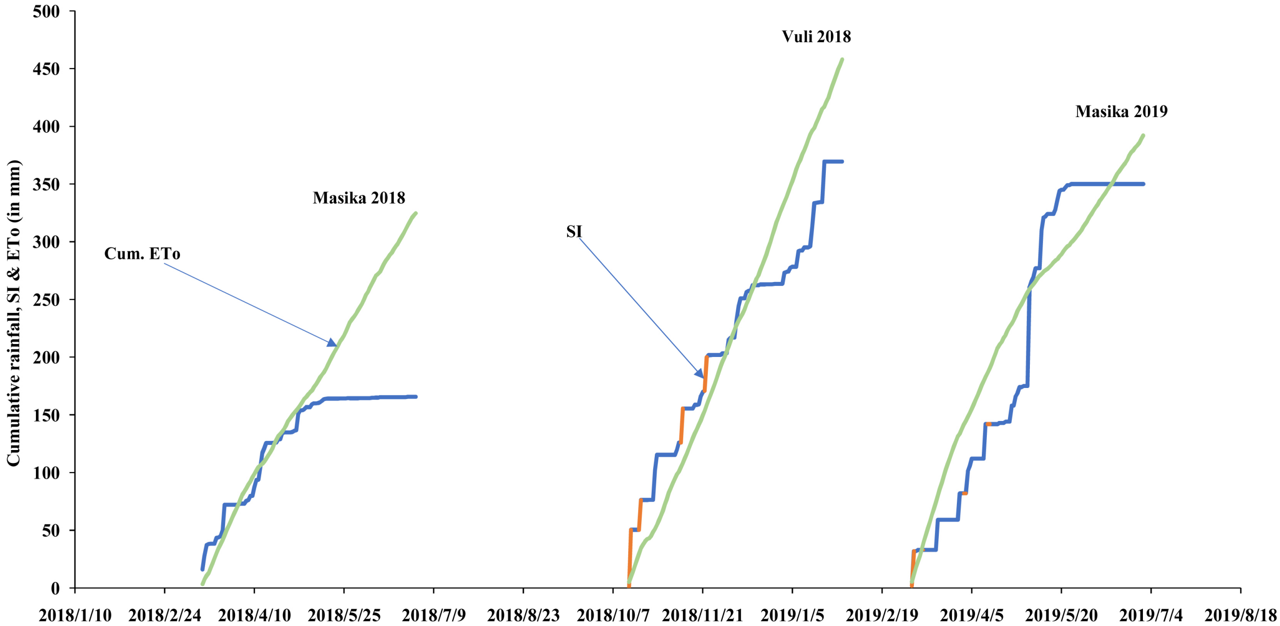

Figure 4. Cumulative daily rainfall (blue and blue plus orange colour lines; orange is irrigation) and ETo (green lines) for Masika 2018, Vuli 2018 and Masika 2019 seasons (the two latter seasons rainfall has SI), recorded from planting to harvest at the experimental field.

3.2. Effects of Management Practices on Soil Moisture Content (SMC)

Soil moisture content varied for the three study seasons (Figure 5). High soil water content was observed throughout the 90 cm profile layer at the beginning of Masika 2018 that gradually decreases towards the end of the season (as the rains stopped). However, for the latter two seasons, the soil water content in the upper 90 cm was much lower at planting (compared to Masika 2018 planting time) and the soil moisture content increased only in the top 30 cm during the season. It also differed among treatments at different layers of the soil profile and with time in all growing seasons ($p = 0.007$). A significant difference in SMC means was between FCM and FC, and between FCM and DD. Interestingly, in all seasons, soil water contents (in the 3 layers) were higher in FCM relative to the other treatments. This indicates that mulching conserved more the soil moisture content in all layers of the soil profile as compared to other treatments in each season. The effect of mulch was more pronounced during about three-quarters of each season and at a depth of 0 - 30 cm. This variation was further noticed in deeper profile layers during the Vuli and Masika 2019 seasons that were affected by rainfall and irrigation (Figure 4 and Figure 5). FC had lower SMC relative to other treatments, although the difference was small from DD, which was observed at 0 - 60 cm layer during the last quarter of the season. The average seasonal SMC was 0.22 cm^3/cm^3, 0.19 cm^3/cm^3 and 0.18 cm^3/cm^3 at 0 - 30 cm layer in FCM, DD and FC plots, respectively. The slightly higher SMC observed in DD compared to FC plots may be attributed to more loose soil structure due to tillage in the DD plots that probably allowed good rainfall water redistribution of the same treatment. This is also observed in low Es recorded in the DD (Chapter 2), especially after rainfall events could be due to redistribution of rainwater deeply in the soil profile as reported by Campbell & Akhtar (1990), thus delaying its escape as evaporation.

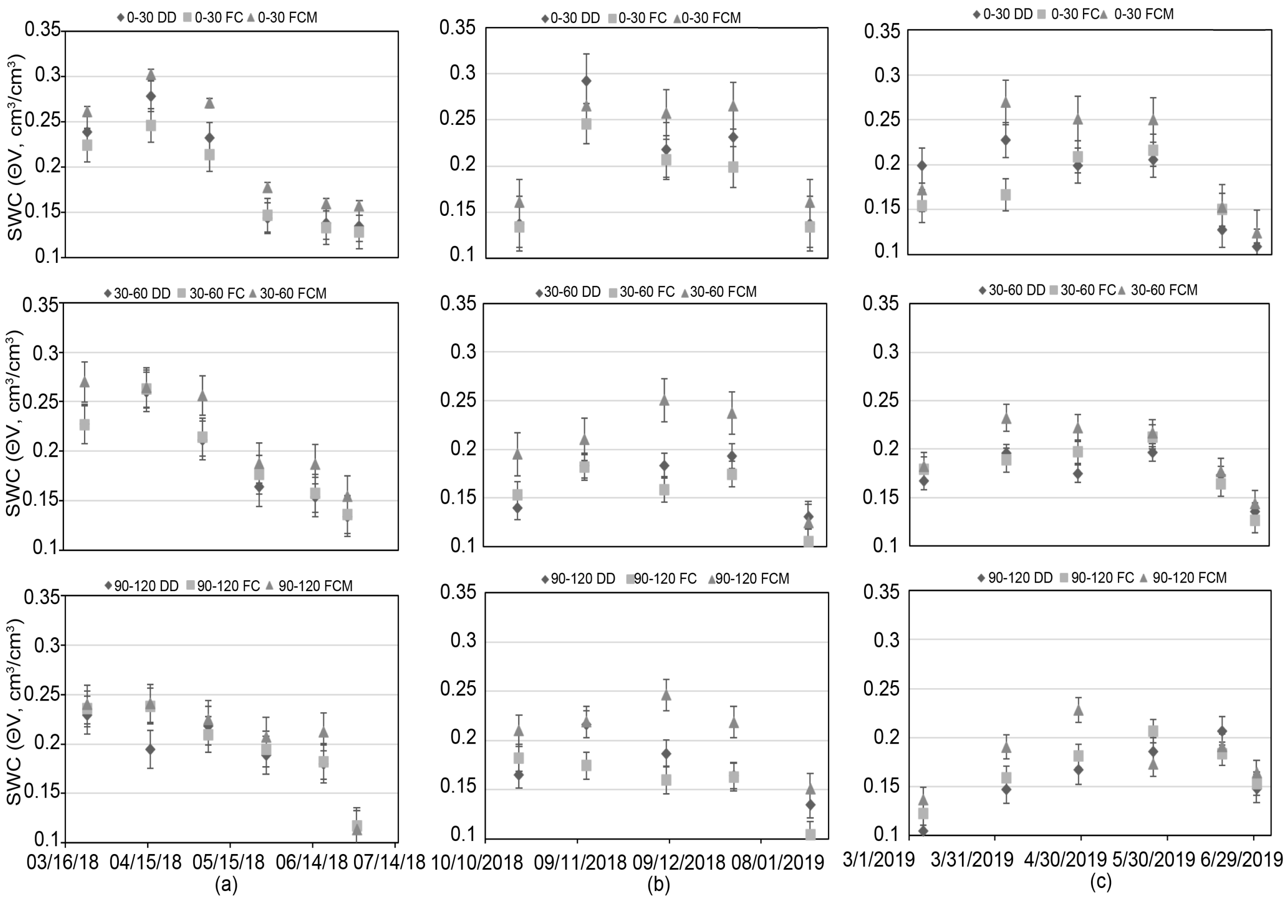

Figure 5. Soil moisture content (SMC, cm³/cm³ of 120 cm soil profile for FCM (cones), DD (diamonds) and FC (squares) treatments measured during the Masika 2018 (a), Vuli 2018 (b) and Masika 2019 (c) seasons. The error bars denote the standard errors of the means.

3.3. Effect of Management Practices on Deep Percolation

The observed deep percolation (DP), i.e. the downward water flux at a depth of 120cm, varied among seasons and treatment (Figure 6). The mean DP loss did not differ significantly among the treatments during the Masika 2018 season. Figure 6 indicates the occurrence of the deep percolation losses in two episodes at the beginning of the season, each time following a rainfall episode. In Vuli 2018 and Masika 2019, DP losses only occurred in the FCM treatment in a few episodes, each following an irrigation event. The DP means differed significantly between FCM and DD and between FCM and FC treatments throughout the two seasons of Vuli 2018 ($p = 0.0056$) and Masika 19 ($p = 0.0265$). There was no statistically significant difference in the seasonal DP between the FC and DD treatments. FCM consistently had a higher DP than other treatments. The seasonal DP loss in FCM was 78 mm in Vuli 2018 and 75 mm in Masika 2019, while DP was negligible (≤5 mm) in the other treatments in both seasons (**Table 2**). The seasonal DP recorded for FC was 5 mm during Vuli 2018 and 3 mm during Masika 2019, while that of DD was 5 mm for during Vuli 2018 and 4 mm during Masika 2019 season.

The DP variation occurred throughout the seasons, but it was much more pronounced during periods of heavy rains in the seasons. The highest DP in FCM plots in all seasons indicates mulch's ability to conserve soil moisture. Because the mulches were maintained in the plots from one season to the other, and the off-season periods were short times (about 2 months), mulched plots had slightly higher soil water content at the beginning of the Vuli 2018 and Masika 2019 seasons (**Figure 5**). The more moisture in the FCM plots stored from the previous seasons than in the FC and DD treatments could be the reason for higher DP in the same FCM than other treatments, although they received the same rainfall. On the other hand, less water and a small effect of DD and FC practices on the soil water content SWC treatments relative to FCM practice during the same seasons could be due to high water loss through soil evaporation as was observed in DD and FC treatments in comparison to FCM.

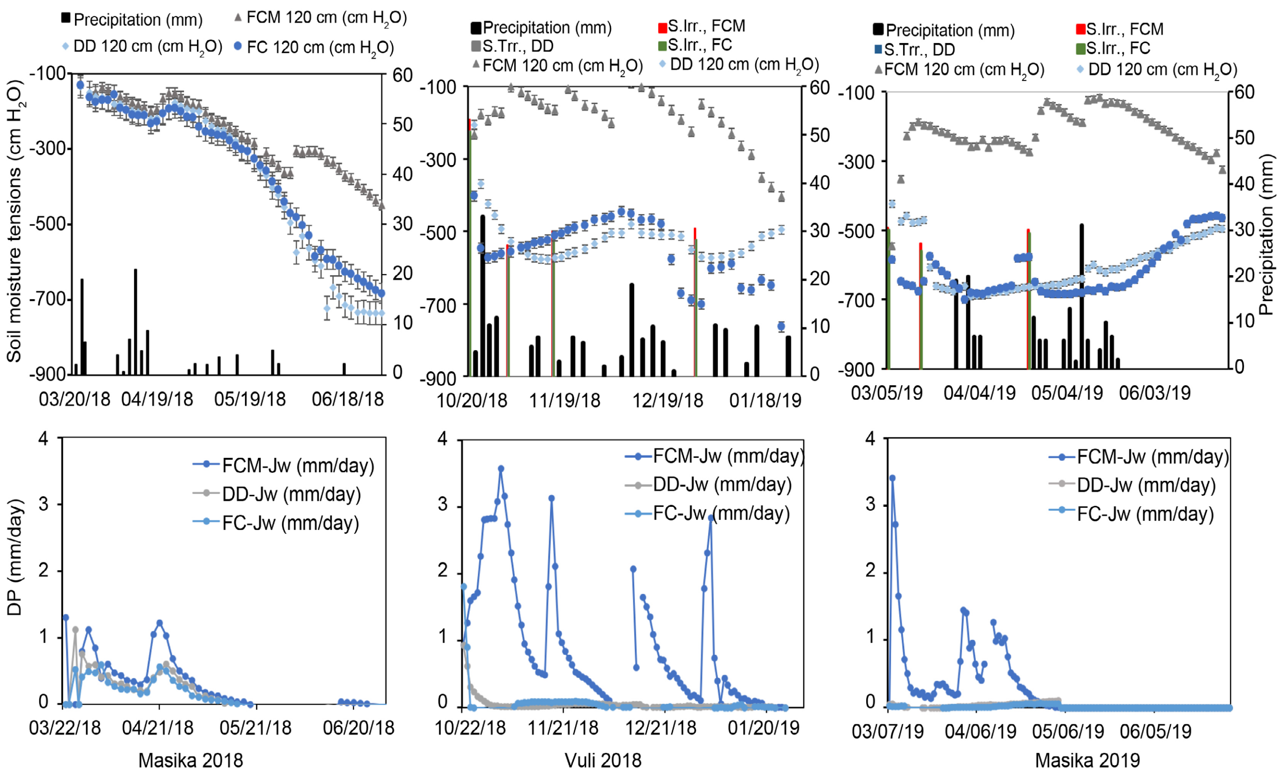

Figure 6. Soil moisture tension (markers in cm H_2O) at 120 cm depth with rainfall and SI (bars in mm) is shown in the upper graphs, and deep percolation (DP) in lower graphs for the Masika 2018 season (left-hand graphs), Vuli 2018 (middle graphs) and Masika 2019 (right-hand graphs).

Table 2. Seasonal rainfall, supplemental irrigation (SI) and deep percolation (DP) for the three consecutive seasons.

Seasons	Treatment	Rainfall (mm)	SI (mm)	DP (mm)
Masika 2018	FCM	165	-	24
	DD	165	-	19
	FC	165	-	15
Vuli 2018	FCM	239	139	79
	DD	239	133	5
	FC	239	132	5
Masika 2019	FCM	177	88	75
	DD	177	84	4
	FC	177	83	−3

3.4. The Soil Water Balance (SWB) Components and the Crop Growth

Figure 7 presents soil water balance components that were used to estimate ET under three treatments in the maize field during the study seasons of Masika 2018, Vuli 2018 and Masika 2019. The SWB components measured during Masika 2018 season are rainfall (P), runoff (RO), deep percolation (DP) and change in soil water content (ΔSWC). The Vuli 2018 and Masika 2019 water balances also contain supplementary irrigation (SI) components.

In Masika 2018 season, the rains practically stopped around 50 days after planting (at the beginning of May), and after that, only some very light rainfall events occurred (Figure 4). During this time, we see that ETo exceeded the rainfall, resulting in a dryer root zone at the end of the season (the crop used the residual moisture). About 71% of the total seasonal rainfall that was recorded during this season evapotranspired. In Vuli 2018 and Masika 2019, however, we started with relatively dry soil, and the evaporative demand was much higher than (P+SI), which led to a slightly negative water balance. At the end of the seasons, the soil did not get dryer than it already was at the beginning, so ET was about equal to P+SI.

The water balance components in Masika 2018 show little difference among the treatments (Figure 7 and Table 2). There was little deep percolation loss during this season. The observed high DP values in FCM plots are linked to the ability of the mulches. The mulches act as a barrier to vapour exchange at the soil surface-atmosphere interface and allow the incoming water into the soils to be taken by plants and the excess water to percolate beyond the root zone. The mulching effect on DP was insignificant during Masika 2018, a rainfed season with a good temporal rainfall distribution from crop germination to maturity.

And crucially, no meaningful runoff was recorded in any of the seasons and treatments, thus presenting an insignificant influence on the SWB. This contradicts the reported high RO (of about 6% of the seasonal rainfall) on the same land and soils as the current study (Bangalala village) as reported by Mul et al. (2006). The measurement in that study was done at a sub-catchment scale of about 24 km^2 using a rainfall-runoff (RAINRU) model that was fitted to the observed rainfall-river discharge time series. The low seasonal RO recorded in the current study contradicting the reported high RO in the area could be due to the effect of the small-scale experimental field that was covered in comparison to the size of the catchment where the high runoff was reported. Besides, such a large scale (24 km^2) catchment includes patches of land that are known to generate more surface runoff than the experimental field with deep soil and thus a high infiltration capacity where the study was conducted. The catchment also contains very shallow soils (often on steep slopes), rock outcrops, and roads that are all known to generate a lot of surface runoff.

From the field experiments, the ET for each treatment was calculated as the only unknown in the mass balance equation based on the incoming and outgoing water fluxes at the root zone (the components of the SWB). The measured seasonal ET was high in Vuli 2018, low in Masika 2018 and lowest during the Masika 2019 season (**Table 3**). The total ET during the study period (three seasons) was 872 mm for FCM, 974 mm for DD and 981 mm for FC (**Table 3**). The high ET during the Vuli season could be attributed to high soil moisture content from a higher volume of rainfall, supplemental irrigation and the high evaporative demand observed in this season relative to other seasons. On the other hand, low ET during the Masika 2018 season is due to the low evaporative demand (ETo) observed throughout that season (**Table 3**). Although the soil was wet, the consistent rainfall that fell throughout the season led to cool weather and low evaporation in all treatments. The seasonal ET results were compared to those measured by the Bowen ratio method from the same study area and during the same seasons as the current study (Nyolei et al., 2021). The field plot in which the BREB ET was estimated was managed as in the FC treatment. However, in the current study, the seasonal ET that the BREB estimated was lower than the observed evapotranspiration from the FC treatment. The underestimation of the ET by the BREB relative to that of the SWB method could partly be due to slight differences in the beginning and end of the ET estimation of experiments. However, the ET differences that could have been caused by methodological differences need more investigation.

The evapotranspiration differed significantly ($p = 0.001$) among the treatments during the Vuli 2018 and Masika 2019 seasons. It did not differ significantly among treatment means during the Masika 2018 season (**Figure 8** and **Table 3**). A significant difference in the ET means during Vuli 2018 and Masika 2019 seasons was observed between FCM and other treatments. The variation between ET means of DD and FC treatments was not statistically significant, although the mean ET was higher in FC practice than in DD practice (**Table 3** and **Figure 8**). The lower average seasonal ET in FCM compared to other treatments throughout the study period is due to the ability of the mulch to reduce soil evaporation, as reported by other studies (Balwinder-Singh et al., 2011; Li et al., 2013; Wang et al., 2018). The slightly higher ET in DD treatment than FC that was observed during the Masika 2019 season (**Table 3**) can be related to the effect of tillage practice on the soil structure (Schwartz, Baumhardt, & Evett, 2010). The study argues that the water loss due to the tillage practice occurs shortly after the installation of the practice into the field, indicating that the soil is looser and thus allows more water through open macropores.

On the other hand, the overall low ET in the DD practice compared to the FC practice could be because the DD practice redistributed more water deeper into the soil through improved soil macropores. With the water percolating deeper in the profile, and because the water loss through evaporation takes place close to the soil surface (Balwinder-Singh et al., 2014; Bonachela et al., 2001) this delays and reduces the process (as discussed in the previous chapter 2, section 2.3.4), thus leading to low ET. The overall highest ET in bare FC plots is associated with the exposure of the plots to direct radiation that allows more water to escape from near the surface through soil evaporation (Es).

Soil evaporation determines the crop ET, and it is important at the beginning of the season when a small or incomplete canopy partially covers the field. Once canopy cover reaches 80% to 90%, or when the fields are covered with mulches, soil evaporation losses are minimized. Because the Es is the unproductive water loss from the field, the higher ET resulted from higher Es during the poor rainfall and high evaporative demand season, resulting in water stress that delays crop growth and causes decreased yield. Crops were much more affected by water stress during Vuli 2018 and Masika 2019 seasons than in Masika 2018. Canopy cover developed rapidly in Masika 2018, reaching 75% cover in 65 days after planting, and there were no statistically significant treatment effects on CC. However, the CC development was slow and reached its maximum of about 70% at 75 days after planting during Vuli 2018 and Masika 2019 (**Figure 8** right). CC development was slightly faster in FCM than in other treatments, but the difference was not statistically significant.

The crop development as observed in the CC evolution among treatments and throughout the seasons also affected final crop yields during Vuli 2018 and Masika 2019. The observed maize grain yields in the 3 treatments ranked in the following order: FCM > DD > FC for the Vuli 2018 and Masika 2019 seasons, and DD recorded slightly lower yields than FC during the Masika 2018 season (**Figure 9**). The highest yields (4 - 6 Mg DM ha^{-1}) were recorded in the Masika 2018 season, the season with good rainfall distribution and its planting after the entire root zone was thoroughly wetted. On the contrary, in the water-stressed season, the yields were lower: 3 - 4 Mg DM ha^{-1} in Masika 2019 and 2 - 4 Mg DM ha^{-1} in Vuli 2018.

The good soil moisture content at planting led to good crop germination and better establishment in the early stages of the Masika 2018 season compared to the latter two seasons, as reflected in the CC data (**Figure 8** right). Also, the good rainfall that was received from planting to close to maturity enabled good crop development, passing through critical growth stages (vegetation, flowering and early grain filling) without water stress is the reason for the observed high yields during the Masika 2018 season. However, a small drought close to the end of the Masika 2018 season caused slight water stress to crops, but it probably had less impact on crop yields as crops had already passed the critical growth stages.

The observed higher maize yields in the FCM treatment throughout the three consecutive seasons affirms the ability of mulches to conserve moisture and make it available for crops even under adverse conditions like that of Vuli seasons or during dry spell periods. The high yields in the FCM practice that was observed during the Masika 2018 season when the water stress was not severe probably reflect the benefit of mulch as a source of nutrients upon decomposition. As it was hypothesized, DD practice seems to have enhanced water redistribution slightly deeper in the profile and made it available for biomass production through plant transpiration. As a result, this improved crop yields in the DD treatment relative to the FC treatment, especially during the two seasons of Vuli 2018 and Masika 2019 that received little (total seasonal) rains with poor temporal distribution. This is also reflected in the SWC and the overall crop yield data. The crop yield was higher in DD than FC during Vuli 2018 and Masika 2019 seasons which were much affected by water stress. This implies that, to some extent, DD treatment conserved more soil moisture as compared to FC that eventually went to transpiration and improved crop yield, as discussed in the next chapter 4. This is evident in the ET results and crop yields (significantly different) between DD and FC treatments during Vuli 2018 and Masika 2019 seasons that were characterized by high evaporative demands (Table 3).

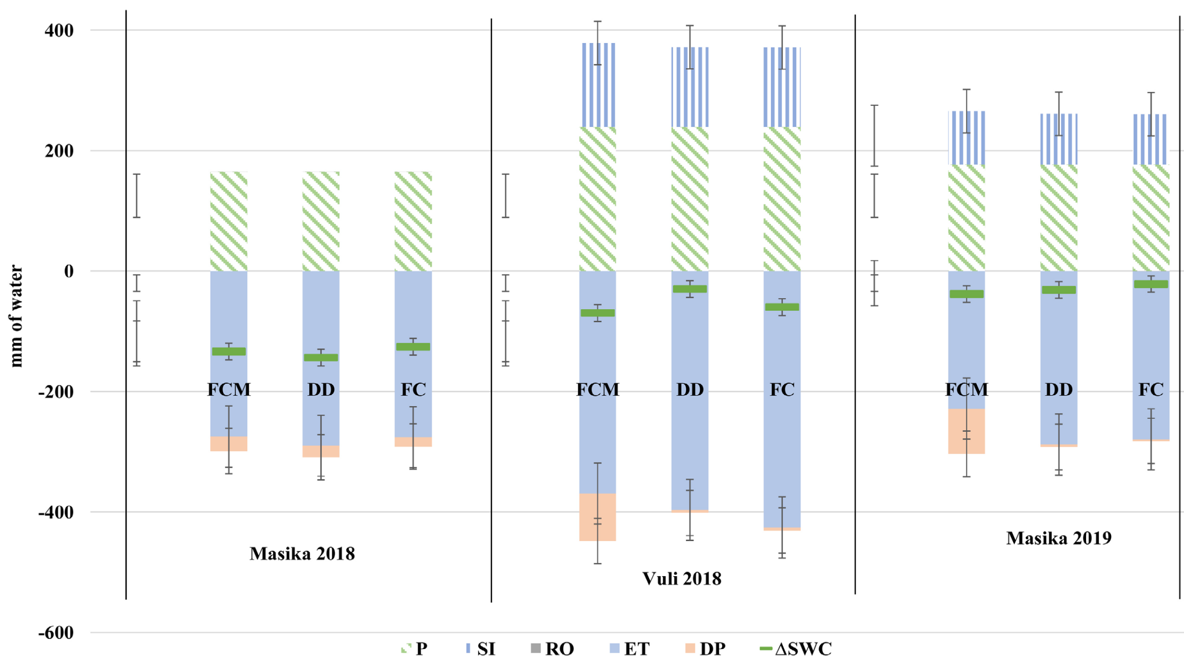

Figure 7. The components of SWB for the three consecutive seasons (Masika 2018, Vuli 2018 and Masika 2019). Inflows into the root zone are shown as positive values, outflows as negative values and the change in root zone water content (ΔSWC) is shown as a green horizontal line. Runoff was small (≤2 mm) in all treatments and seasons. Error bars denote standard errors of the means.

Table 3. Observed actual evapotranspiration (mm) based on the SWB method for three treatments, FCM, DD and FC, for Masika 2018, Vuli 2018 and Masika 2019 seasons, as compared to the calculated seasonal ETo and the ET measured with the Bowen Ratio Energy Balance (BREB) method by Nyolei et al. (2021).

Seasons	FCM (ET, mm)	DD (ET, mm)	FC (ET, mm)	BREB (ET, mm)	ETo, mm
Msk[2] 2018	274.7	290.0	275.9	266.9	324.7
Vuli 2018	369.2	396.6	425.7	347.9	457.9
Msk 2019	228.4	287.7	279.1	188.3	392.2
Total ET	872.3	974.4	980.7		

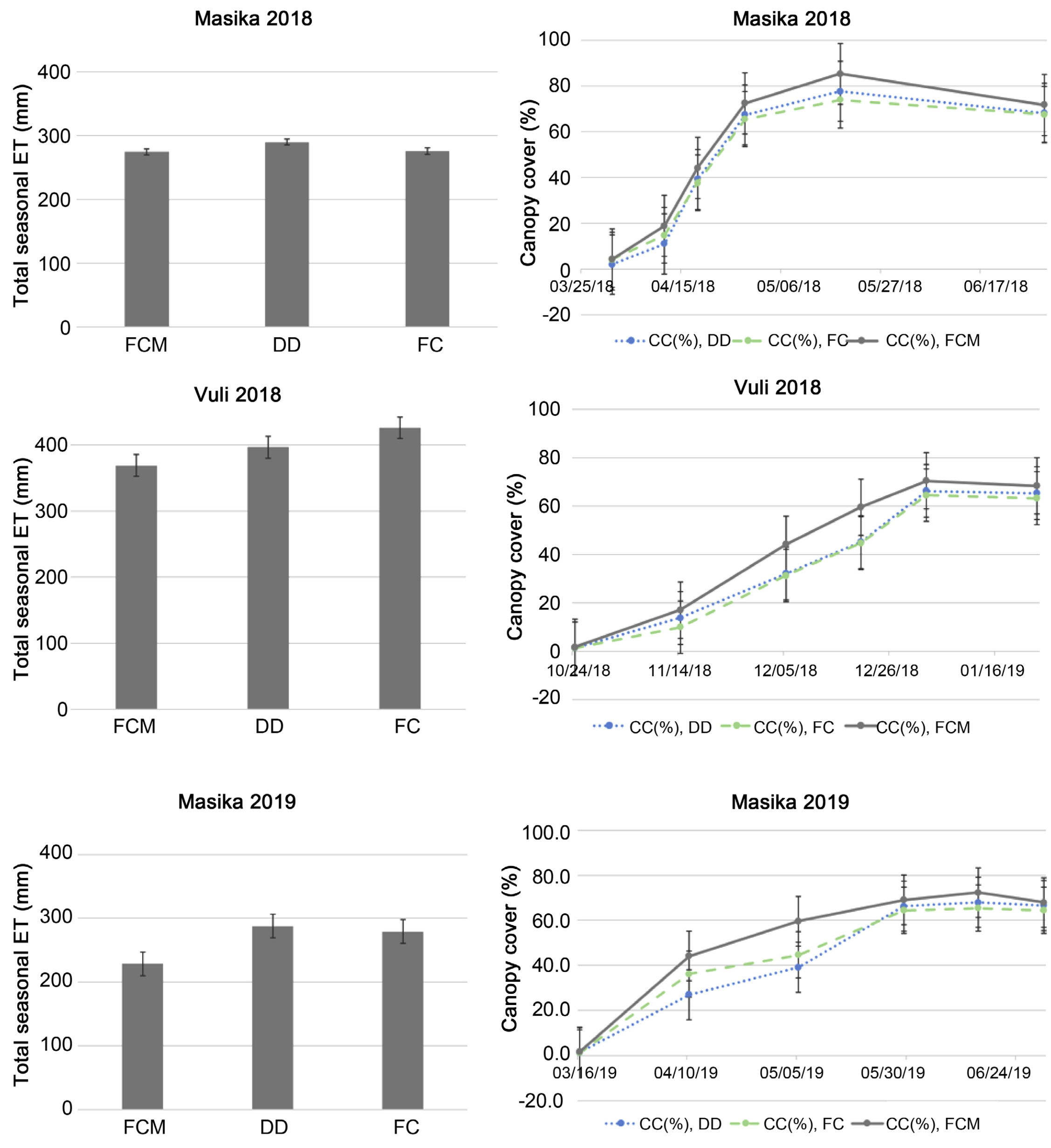

Figure 8. Observed seasonal ET (left) and evolution of canopy cover (right) under FCM, DD and FC management practices during Masika 2018, Vuli 2018 and Masika 2019 seasons. Error bars denote ± standard errors of the means.

[2]Masika.

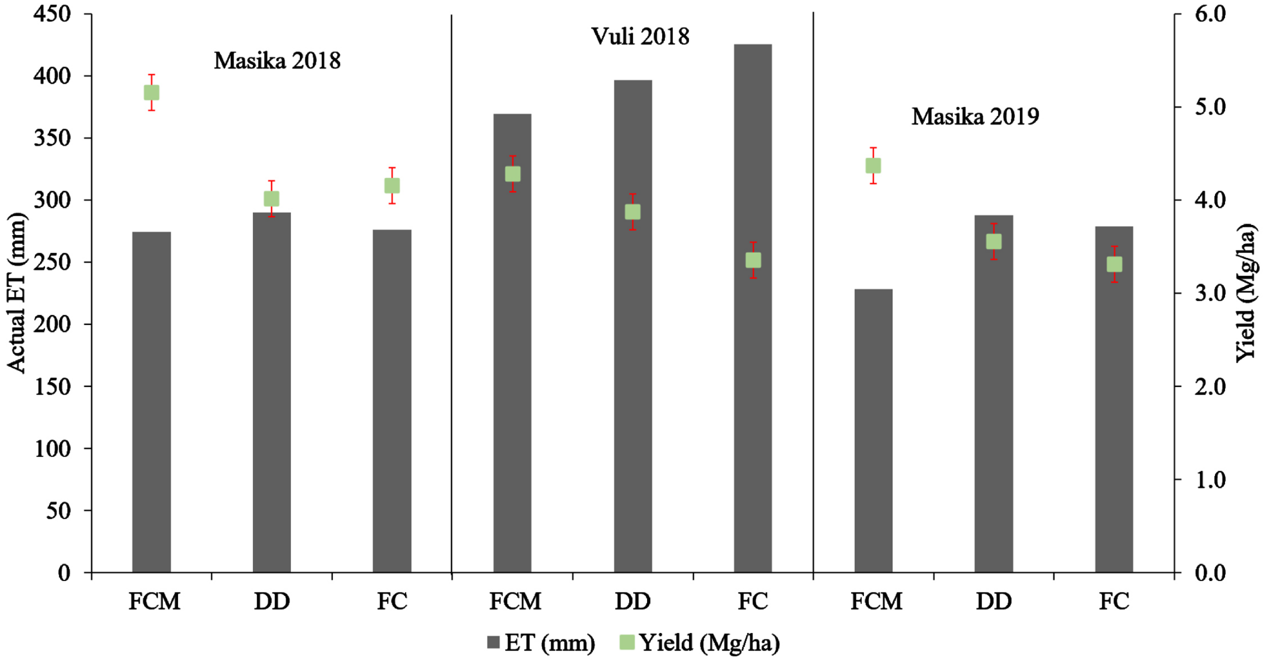

Figure 9. Field observed seasonal ET (mm) (grey bars and left Y-axis) and grain yield (Mg/ha) (green symbols and right Y-axis) per treatment for three consecutive seasons of Masika 2018, Vuli 2018 and Masika 2019. Error bars denote ± standard errors of the means.

4. Conclusion

The ET (mm) was estimated using the soil water balance approach during three consecutive seasons, Masika and Vuli 2018 and Masika 2019. There was a variation among the ET means of the treatments and the seasons.

The FCM effect on ET was observed in the dry and water-stressed seasons of Vuli 2018 and Masika 2019, with 14% and 18% reduction. The high SWC in the FCM as observed especially during the water-stressed seasons, with a low ET in the same treatment (**Figure 9**) affirms that the mulch reduces soil evaporation that probably goes to Tr. This enhances quick crop development during the vegetative growth stage and results in improved crop development and crop yields (**Figure 9**).

The higher deep percolation in the FCM plots that were recorded during the seasons of Vuli 2018 and Masika 2019 that received SI suggest excess water in the mulch plots went into DP. Due to the mulch that reduces soil evaporation and conserves moisture for plant uptake, plots with mulch need to be supplied with less supplementary irrigation to enhance plant water uptake without increasing DP losses in such areas where irrigation water is in short supply.

The DD treatment did not affect the ET reduction, although it reduced soil evaporation by 17% relative to the control FC treatment during the first season (chapter 2). However, the higher SMC observed in the DD practice and also the higher ET recorded in the same practice during the Vuli 2018 and Masika 2019 seasons indicates; first, the good water redistribution feature of the tilled soil (in DD), and second, the possibility that the soil moisture that was concentrated deeper in the root zone was used for the biomass production. This is reflected both in the green canopy cover and the final crop grain yield, which are higher in the tilled plots of DD than in undisturbed soil plots of FC.

Since the little rainfall that comes in these semiarid areas, such as the Makanya catchment, is lost through evapotranspiration and because the farming in the area is mostly rainfed, this has led to reduced crop yield and sometimes crop failure. However, the different agricultural management practices tested in this study indicate that FCM can be used to reduce evapotranspiration (unproductive part) and conserve soil moisture that would become available for plants, especially during dry spells improve the yield. Although DD may seem tedious, to some extent, it improves the moisture content of the soil used by plants, especially during the dry spells of the bad rainfall seasons and hence improves the crop yield relative to the farmers' traditional cultivation method (FC).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Ahmed, S. A., Diffenbaugh, N. S., Hertel, T. W., Lobell, D. B., Ramankutty, N., Rios, A. R., & Rowhani, P. (2011). Climate Volatility and Poverty Vulnerability in Tanzania. *Global Environmental Change, 21,* 46-55. https://doi.org/10.1016/j.gloenvcha.2010.10.003

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56*. FAO.

Anapalli, S. S., Ahuja, L. R., Gowda, P. H., Ma, L., Marek, G., Evett, S. R., & Howell, T. A. (2016). Simulation of Crop Evapotranspiration and Crop Coefficients with Data in Weighing Lysimeters. *Agricultural Water Management, 177,* 274-283. https://doi.org/10.1016/j.agwat.2016.08.009

Anderson, R. G., Zhang, X., & Skaggs, T. H. (2017). Measurement and Partitioning of Evapotranspiration for Application to Vadose Zone Studies. *Vadose Zone Journal, 16,* 1-9. https://doi.org/10.2136/vzj2017.08.0155

Angulo-Jaramillo, R., Bagarello, V., Iovino, M., & Lassabatere, L. (2016). *Infiltration Measurements for Soil Hydraulic Characterization*. Springer International Publishing. https://doi.org/10.1007/978-3-319-31788-5

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., et al. (2001). FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bulletin of the American Meteorological Society, 82,* 2415-2434.

https://doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2

Balwinder-Singh, Eberbach, P. L., & Humphreys, E. (2014). Simulation of the Evaporation of Soil Water beneath a Wheat Crop Canopy. *Agricultural Water Management, 135,* 19-26. https://doi.org/10.1016/j.agwat.2013.12.008

Balwinder-Singh, Eberbach, P. L., Humphreys, E., & Kukal, S. S. (2011). The Effect of Rice Straw Mulch on Evapotranspiration, Transpiration and Soil Evaporation of Irrigated Wheat in Punjab, India. *Agricultural Water Management, 98,* 1847-1855. https://doi.org/10.1016/j.agwat.2011.07.002

Ben-Asher, J., & Ayars, J. E. (1990). Deep Seepage under Nonuniform Sprinkler Irrigation. II: Field Data. *Journal of Irrigation and Drainage Engineering, 116,* 363-373. https://doi.org/10.1061/(ASCE)0733-9437(1990)116:3(363)

Bonachela, S., Orgaz, F., Villalobos, F. J., & Fereres, E. (2001). Soil Evaporation from Drip-Irrigated Olive Orchards. *Irrigation Science, 20,* 65-71. https://doi.org/10.1007/s002710000030

Campbell, J. A. & Akhtar, M. E. (1990). Impact of Deep Tillage on Soil Water Regimes in Rainfed Areas. In M. I. Akhtar, & M. E. Nizami (Eds.), *Soil Physics—Application under Stress Environments* (pp. 267-275). Pakistan Agricultural Research Council (PARC).

Chanasyk, D. S., Mapfumo, E., & Chaikowsky, C. L. A. (2006). Estimating Actual Evapotranspiration Using Water Budget and Soil Water Reduction Methods. *Canadian Journal of Soil Science, 86,* 757-766. https://doi.org/10.4141/S05-063

Crescimanno, G., & Iovino, M. (1995). Parameter Estimation by Inverse Method Based on One-Step and Multi-Step Outflow Experiments. *Geoderma, 68,* 257-277. https://doi.org/10.1016/0016-7061(95)00049-8

Durner, W., & Iden, S. C. (2011). Extended Multistep Outflow Method for the Accurate Determination of Soil Hydraulic Properties near Water Saturation. *Water Resources Research, 47,* W08526. https://doi.org/10.1029/2011WR010632

Eching, S. O., Hopmans, J. W., & Wendroth, O. (1994). Unsaturated Hydraulic Conductivity from Transient Multistep Outflow and Soil Water Pressure Data. *Soil Science Society of America Journal, 58,* 687-695. https://doi.org/10.2136/sssaj1994.03615995005800030008x

Enfors, E., Barron, J., Makurira, H., Rockström, J., & Tumbo, S. (2011). Yield and Soil System Changes from Conservation Tillage in Dryland Farming: A Case Study from North Eastern Tanzania. *Agricultural Water Management, 98,* 1687-1695. https://doi.org/10.1016/j.agwat.2010.02.013

FAO (2001). *Soil Moisture Management*. USDA Soil Conservation Service.

Fischer, B. M. C., Mul, M. L., & Savenije, H. H. G. (2013). Determining Spatial Variability of Dry Spells: A Markov-Based Method, Applied to the Makanya Catchment, Tanzania. *Hydrology and Earth System Sciences, 17,* 2161-2170. https://doi.org/10.5194/hess-17-2161-2013

Gebler, S., Hendricks Franssen, H. J., Pütz, T., Post, H., Schmidt, M., & Vereecken, H. (2015). Actual Evapotranspiration and Precipitation Measured by Lysimeters: A Comparison with Eddy Covariance and Tipping Bucket. *Hydrology and Earth System Sciences, 19,* 2145-2161. https://doi.org/10.5194/hess-19-2145-2015

Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., Voß, F., Arnell, N. W. et al. (2011). Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results. *Journal of Hydrometeorology, 12,* 869-884. https://doi.org/10.1175/2011JHM1324.1

Hillel, D. (1980). Soil Water: Content and Potential. In *Fundamentals of Soil Physics* (pp. 123-165). Academic Press. https://doi.org/10.1016/B978-0-08-091870-9.50012-1

Hopmans, J. W., Šimůnek, J., Romano, N., & Durner, W. (2018). Inverse Methods. *Methods of Soil Analysis, Part 4: Physical Methods* (pp. 963-1008). Wiley. https://doi.org/10.2136/sssabookser5.4.c40

Joshi, P. (1987). Effect of Surface Irrigation on Land Degradation. *Indian Journal of Agricultural Economics, 42,* 416-423.

Li, S. X., Wang, Z. H., Li, S. Q., Gao, Y. J., & Tian, X. H. (2013). Effect of Plastic Sheet Mulch, Wheat Straw Mulch, and Maize Growth on Water Loss by Evaporation in Dryland Areas of China. *Agricultural Water Management, 116,* 39-49. https://doi.org/10.1016/j.agwat.2012.10.004

Li, S., Kang, S., Li, F., & Zhang, L. (2008). Evapotranspiration and Crop Coefficient of Spring Maize with Plastic Mulch Using Eddy Covariance in Northwest China. *Agricultural Water Management, 95,* 1214-1222. https://doi.org/10.1016/j.agwat.2008.04.014

Li, S., Kang, S., Zhang, L., Zhang, J., Du, T., Tong, L., & Ding, R. (2016). Evaluation of Six Potential Evapotranspiration Models for Estimating Crop Potential and Actual Evapotranspiration in Arid Regions. *Journal of Hydrology, 543,* 450-461. https://doi.org/10.1016/j.jhydrol.2016.10.022

Li, S., Li, Y., Lin, H., Feng, H., & Dyck, M. (2018). Effects of Different Mulching Technologies on Evapotranspiration and Summer Maize Growth. *Agricultural Water Management, 201,* 309-318. https://doi.org/10.1016/j.agwat.2017.10.025

Li, S., Zhang, L., Kang, S., Tong, L., Du, T., Hao, X., & Zhao, P. (2015). Comparison of Several Surface Resistance Models for Estimating Crop Evapotranspiration over the Entire Growing Season in Arid Regions. *Agricultural and Forest Meteorology, 208,* 1-15. https://doi.org/10.1016/j.agrformet.2015.04.002

Luhunga, P. M., Kijazi, A. L., Chang'a, L., Kondowe, A., Ng'ongolo, H., & Mtongori, H. (2018). Climate Change Projections for Tanzania Based on High-Resolution Regional Climate Models from the Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa. *Frontiers in Environmental Science, 6,* Article 122. https://doi.org/10.3389/fenvs.2018.00122

Makurira, H., Savenije, H. H. G., Uhlenbrook, S., Rockström, J., & Senzanje, A. (2011). The Effect of System Innovations on Water Productivity in Subsistence Rainfed Agricultural Systems in Semi-Arid Tanzania. *Agricultural Water Management, 98,* 1696-1703. https://doi.org/10.1016/j.agwat.2011.05.003

Miralles, D. G., Holmes, T. R. H., De Jeu, R. A. M., Gash, J. H., Meesters, A. G. C. A., & Dolman, A. J. (2011). Global Land-Surface Evaporation Estimated from Satellite-Based Observations. *Hydrology and Earth System Sciences, 15,* 453-469. https://doi.org/10.5194/hess-15-453-2011

Mul, M. L., Kemerink, J. S., Vyagusa, N. F., Mshana, M. G., van der Zaag, P., & Makurira, H. (2011). Water Allocation Practices among Smallholder Farmers in the South Pare Mountains, Tanzania: The Issue of Scale. *Agricultural Water Management, 98,* 1752-1760. https://doi.org/10.1016/j.agwat.2010.02.014

Mul, M. L., Savenije, H. H. G., Uhlenbrook, S., & Voogt, M. P. (2006). Hydrological Assessment of Makanya Catchment in South Pare Mountains, Semiarid Northern Tanzania. In *Climate Variability and Change-Hydrological Impacts, Proceedings of the Fifth FRIEND World Conference* (pp. 37-43). IAHS Publ.

Mutiro, J., Makurira, H., Senzanje, A., & Mul, M. L. (2006). Water Productivity Analysis for Smallholder Rainfed Systems: A Case Study of Makanya Catchment, Tanzania. *Physics and Chemistry of the Earth, 31,* 901-909. https://doi.org/10.1016/j.pce.2006.08.019

Nyolei, D., Diels, J., Mbilinyi, B., Mbungu, W., & van Griensven, A. (2021). Evapotranspiration Simulation from a Sparsely Vegetated Agricultural Field in a Semi-Arid Agro-Ecosystem Using Penman-Monteith Models. *Agricultural and Forest Meteorology, 303,* Article ID: 108370. https://doi.org/10.1016/j.agrformet.2021.108370

Pereira, L. S., Paredes, P., E, E. D., Inchenkova, O. P., Teodoro, P. R., & Horst, M. G. (2009). Irrigation Scheduling Strategies for Cotton to Cope with Water Scarcity in the Fergana Valley, Central Asia. *Agricultural Water Management, 96,* 723-735. https://doi.org/10.1016/j.agwat.2008.10.013

Pütz, T., Kiese, R., Wollschläger, U., Groh, J., Rupp, H., Zacharias, S. et al. (2016). TERENO-SOILCan: A Lysimeter-Network in Germany Observing Soil Processes and Plant Diversity Influenced by Climate Change. *Environmental Earth Sciences, 75,* Article No. 1242. https://doi.org/10.1007/s12665-016-6031-5

Rockström, J., & Barron, J. (2007). Water Productivity in Rainfed Systems: Overview of Challenges and Analysis of Opportunities in Water Scarcity Prone Savannahs. *Irrigation Science, 25,* 299-311. https://doi.org/10.1007/s00271-007-0062-3

Rockström, J., Barron, J., & Fox, P. (2003). Water Productivity in Rain-Fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-Prone Tropical Agroecosystems. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement* (pp. 145-162). CAB International. https://doi.org/10.1079/9780851996691.0145

Rowhani, P., Lobell, D. B., Linderman, M., & Ramankutty, N. (2011). Climate Variability and Crop Production in Tanzania. *Agricultural and Forest Meteorology, 151,* 449-460. https://doi.org/10.1016/j.agrformet.2010.12.002

Saito, H., Šimůnek, J., & Mohanty, B. P. (2006). Numerical Analysis of Coupled Water, Vapor, and Heat Transport in the Vadose Zone. *Vadose Zone Journal, 5,* 784-800. https://doi.org/10.2136/vzj2006.0007

Schneider, F., Don, A., Hennings, I., Schmittmann, O., & Seidel, S. J. (2017). The Effect of Deep Tillage on Crop Yield—What Do We Really Know? *Soil and Tillage Research, 174,* 193-204. https://doi.org/10.1016/j.still.2017.07.005

Schwartz, R. C., Baumhardt, R. L., & Evett, S. R. (2010). Tillage Effects on Soil Water Redistribution and Bare Soil Evaporation throughout a Season. *Soil and Tillage Research, 110,* 221-229. https://doi.org/10.1016/j.still.2010.07.015

Shen, J. (1981). *Discharge Characteristics of Triangular-Notch Thin-Plate Weirs* (pp. 1-45). US Geological Survey Water Supply Paper.

Sillon, J. F., Richard, G., & Cousin, I. (2003). Tillage and Traffic Effects on Soil Hydraulic Properties and Evaporation. *Geoderma, 116,* 29-46. https://doi.org/10.1016/S0016-7061(03)00092-2

Singh, S., Boote, K. J., Angadi, S. V, & Grover, K. K. (2017). Estimating Water Balance, Evapotranspiration and Water Use Efficiency of Spring Safflower Using the CROPGRO Model. *Agricultural Water Management, 185,* 137-144. https://doi.org/10.1016/j.agwat.2017.02.015

URT (2007). *National Adaptation Programme of Action.* NAPA.

USBR (United States Bureau of Reclamation) (2001). Water Measurement Manual, 3rd Edition Revised Reprinted. Technical report, Water Resources Research Laboratory, US Department of the Interior (p. 317). https://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/index.htm

van Dam, J. C., Stricker, J. N. M., & Droogers, P. (1994). Inverse Method to Determine Soil Hydraulic Functions from Multistep Outflow Experiments. *Soil Science Society of America Journal, 58,* 647-652. https://doi.org/10.2136/sssaj1994.03615995005800030002x van Genuchten, M. T. (1980). A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils1. *Soil Science Society of America Journal, 44,* 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wang, J., Zhang, Y., Gong, S., Xu, D., Juan, S., & Zhao, Y. (2018). Evapotranspiration, Crop Coefficient and Yield for Drip-Irrigated Winter Wheat with Straw Mulching in North China Plain. *Field Crops Research, 217,* 218-228. https://doi.org/10.1016/j.fcr.2017.05.010

Watanabe, K., Yamamoto, T., & Yamada, T. (2004). Changes in Seasonal Evapotranspiration, Soil Water Content, and Crop Coefficients in Sugarcane, Cassava, and Maize Fields in Northeast Thailand. *Agricultural Water Management, 67,* 133-143. https://doi.org/10.1016/j.agwat.2004.02.004

Wilson, K. B., Hanson, P. J., Mulholland, P. J., Baldocchi, D. D., & Wullschleger, S. D. (2001). A Comparison of Methods for Determining Forest Evapotranspiration and Its Components: Sap-Flow, Soil Water Budget, Eddy Covariance and Catchment Water Balance. *Agricultural and Forest Meteorology, 106,* 153-168. https://doi.org/10.1016/S0168-1923(00)00199-4

Zhang, Z., Tian, F., Hu, H., & Yang, P. (2014). A Comparison of Methods for Determining Field Evapotranspiration: Photosynthesis System, Sap Flow, and Eddy Covariance. *Hydrology and Earth System Sciences, 18,* 1053-1072. https://doi.org/10.5194/hess-18-1053-2014