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Management of Crop Water Stress in the Tropics and Subtropics

Effects of water availability and water management on the performance of NERICA 4 under rainfed conditions in semi-arid areas, Tanzania

Thesis prepared for the degree Master of Science

Biobased Products and Bioenergy M.Sc.

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Abstract

Rice is one of the most important staple crops. This crop is a rapidly growing food source and has become a commodity of strategic significance especially in Sub-Saharan Africa. In semi-arid areas in Africa soil degradation and droughts are increasingly productivity-reducing problems.

The idea of this thesis is to identify possibilities to grow upland rice in seasonal drought prone areas in Tanzania with minimal water management. The effects of minimal water management in case of modifying the soil surface to collect and save water; by adding a minimum amount of water or to decrease evaporation by an adapted weeding management, may help to grow a successful rice crop under local conditions.

Hereby the upland rice variety NERICA 4, which was developed to show resistance to African rice pests, diseases and water stress combined with high yield potentials, was used for investigating its performance under the management practices which were implemented in this study. This upland variety will be tested under rainfed conditions for the Dodoma region (592 mm, October - May), rainfed conditions with tied-ridging, tied-ridging combined with additional irrigation to keep soil moisture above the permanent wilting point of the soil (life saving irrigation), life saving irrigation without tied ridges and under fulfilled crop water requirements. Those options were combined with time based weeding strategies. Variation in soil moisture contents, leaf area, specific leaf area (SLA), biomasspartitioning, yield determining components like number of productive tillers and spikelets, grain yield, harvest index (HI), yield loss and water use efficiency (WUE) in response to the water management were investigated. Modification of the soil surface influenced soil moisture characteristics and is related to changed yield determining components. The weeding strategy did also lead to changed soil moisture values and microclimate within the canopy but is not responsible for significantly changed grain yields. The poor rainfall distribution in the growing season 2015 provoked total failure at the rainfed treatments and caused yield loss and thus low water use efficiencies for the treatments with life saving irrigation.

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AWP	Available water capacity
bar	1 bar = 10^5 Pascal (Pa)
°C	Degree Celsius
Ca	Calcium
cm	Centimeter
CW	Clean weeding
CWR	Crop water requirements
d	Day
DAS	Days after sowing
Deg	Degree
DM	Dry matter
FC	Field capacity
FDR	Frequency domain reflectometry
FI	Full irrigation, (treatment with full water supply)
FW	Farmer`s weeding
f_w	Fraction of the surface wetted
g	Gram
ha	Hectare
HI	Harvest Index
K	Potassium
KAK_{pot}	Potential cation exchange capacity
kg	Kilogram
kPa	Kilopascal
$K_{c\ ini}$	Crop coefficient for the initial stage
l	Liter
LAI	Leaf area index
LSI	Life saving irrigation
m	Meter
m^2	Squaremeter
mbar	Millibar
Mg	Magnesium
mg	Milligram
Mmol	Millimol (mmolc, c = charge)
N	Nitrogen
Na	Sodium
NERICA	New Rice for Africa
O	Oxygen
P	Phosphorus
Pa	Pascal
pH	Negative decade logarithm to base 10 of the concentration
PWP	Permanent wilting point

R	Rainfed treatments	SSA	Sub-Saharan Africa
SLA	Specific leaf area		
t	Tons		
TDR	Time domain reflectometry		
TGW	Thousand grain weight		
TR	Tied ridges		
WC	Water column		
µS	Microsiemens		

1 Introduction

Drought as well as soil degradation is an increasing productivity-reducing problem in semi-arid East Africa (Slegers, M. F. W., 2008). Rainfall cannot be influenced but should not be the major threat for food insecurity any longer. Farmers need to modify their land management practices to decrease the influence of water shortage, soil type and location on their sustainable and successful crop production. Rice (*Oryza Sativa* L.) is worldwide one of the three most important staple crops after wheat and maize (Bandyopadhay and Roy, 1992). For millions of people in Sub-Saharan Africa (SSA) this main staple food is no longer a luxury food for households with lower income, it is rather a major source for calories. Proportionally to the higher-income households, the low income households spend more of their financial cash resources for rice. In urban areas the demand for rice is rising because of the opportunity costs of women’s labor and the easy and rapid cooking of rice. The consumption of rice in SSA is expected to increase 5 % per year from 2012. This is equivalent to 1.2 Mio. tons of milled rice which need to be either imported or produced (Seck et al., 2013). Rice is a rapidly growing food source and has become a commodity of strategic significance especially in SSA.

Seck et al. (2012) says that water intensive rice cropping systems are not suited to seasonal drought prone areas. 450 - 500 mm of precipitation are required during the growing period (Food Crop Diversification Support Project, 2010; Hijmans and Serraj, 2009; Matsumoto et al., 2014). According to this amount of water needed to grow upland rice, Dodoma region (Tanzania) with a long term average precipitation of 429.4 mm for the growing season from January until May is therefore marginal suitable. De Datta and Surajit K. (1981) named the amount of 200 mm per month as minimal water demand. Hence in addition to the total amount of available water, the frequency and the temporal rainfall distribution are yield determining parameters.

1.1 Growing upland rice in semi-arid regions (Dodoma region, Tanzania)

Rainfed cropping systems in semi-arid areas in Tanzania are prone to water shortage due to the amount of water and the variability of rainfall. Additionally to the inadequate soil moisture, low soil fertility is a major determinant on the productivity of rainfed systems. The average amount of precipitation for Tanzania is 1071 mm/year. The semi-arid Dodoma region has one rainy season starting in October ending in May (Mahoo et al., 2015). The mean rainfall, which was measured over a time of 20 years, for one season is 591.9 mm, may reach a minimum of 326.3 mm, but could also reach an amount of 881.6 mm (Table 1). From December until March the rainfall exceeds 111 mm per month. During that season it rained at 77 days. At 18 days during that season it rained more than 10 mm per day. Heavy rainfalls may cause run-off and hereby soil degradation and water loss, which could improve plant development.

Table 1: Summary of long term (20 years) rainfall characteristics for Hombolo [5° 55´S, 35° 50´E] (Mahoo et al., 2015).

Month		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Season
Rainfall (mm)	Min	0.0	0.0	0.0	35.7	39.7	7.0	0.8	0.0	326.3
	Mean	3.8	33.9	113.5	133.7	121.7	111.4	61.6	5.9	591.9
	70%[1]	0.0	9.6	60.8	83.8	81.8	82.0	20.8	2.8	518.0
	Max	43.6	88.5	290.5	293.7	253.1	180.0	212.2	24	881.6
Wet days	3mm +	2	2	6	8	7	7	5	0	37
	5mm+	1	1	5	6	6.4	5	3	0	22
	10mm+	1	1	3	4	4	2	2.2	0	18
Longest Dry spell (days)	Min	21	5	5	4	3	4	1	8	
	30%[2]	31	27	19	11	17	20	15	31	
	Mean	31	19	17	8	12	14	13	29	
	Max	31	30	41	17	25	27	34	48	

1=Probability of exceeding; 2= Risk of occurrence

Erratic and poor rainfall distribution can be counteracted by soil management practices such as minimal water management in case of modifying the soil surface to collect and save water, by adding a minimum amount of water or to decrease evaporation by an adapted weeding management. Possibilities need to be identified to grow a successful rice crop under local conditions. Climate variability should not play the key role on food insecurity and low income (Slegers, M. F. W., 2008) and human induced cause need to decrease.

New Rice for Africa (NERICA) is a crossing of exotic Asian rice (*Oryza sativa* L.) and indigenous African rice (*Oryza glaberrima*). In the 1990s NERICA was developed by African Rice Development Centre (WARDA). Those NERICA varieties are described as well adapted to the African environment. They show resistance to African rice pests, diseases and water stress combined with high yield potentials (Kijima and Sserunkuuma, 2008). Kijima and Sserunkuuma, (2008) name the amount of 1 t/ha for traditional rice in Africa and expect an average of 2.6 t/ha of NERICA within low-input rainfed conditions which would be a good improvement. The expected yield without fertilizer for NERICA 4, which was used for our research, is 1.5 t/ha but can reach 4 t/ha with good management and moderate soil fertility (Food Crop Diversification Support Project, 2010). In conclusion the NERICA varieties can be a contribution to the food security and poverty reduction.

1.2 Background and objectives of this study

This Master study, which is embedded in a PhD study, aims to assess the potential of upland rice productivity increase in smallholder production systems in Dodoma region (Figure 1). The field trial was conducted at ARI-Makutupora, a station of the Tanzanian Agricultural Research Institute from January to May 2015. Major challenges for local farmers are erratic rainfall events (see Table 1 and Figure 13), poor rainfall distribution and drought spells during the growing period (Table 1). In order to counteract these yield reducing effects soil water conservation methods need to be applied. The focus of this study lies on the investigation of such soil water management practices, namely tied ridges and time based weeding strategies. Tied ridges are a modification of the soil surface and help to improve water and soil conservation. The weeding component will help to evaluate the effect of evaporation versus water use of the weeds within the system. The idea of life saving irrigation is to add less water than needed by crop water requirement estimation but to avoid that the soil moisture is lower than the permanent wilting point.

The upland rice variety NERICA 4 was used for investigating its performance under the management practices which were implemented in this study. The seeds were obtained from Africa Rice. The NERICA variety was tested under rainfed conditions, rainfed conditions with tied-ridging as a water conserving measure, tied-ridging with life saving irrigation based on soil moisture monitoring, life saving conditions without tied ridges and under crop water requiring conditions. Those five options were combined with and without weeding as locally adopted practice. The main objective is to analyze the impact of these measures on soil water conservation and the yield potential of upland rice.

Figure 1: Map of Tanzania. Red dot marking the capital Dodoma. Nearby, our field experiments were conducted (FAO).

The gained dataset will help to evaluate the required conditions to include upland rice into the cropping system and can help to determine the amount of water required to grow rice successfully under local climate conditions. Based on current rainfall patterns of Dodoma, it will be investigated how much irrigation water, in addition to precipitation, is required in order to achieve a certain desired yield. Additionally the effects of weeding and of minimal run-off management will be focused in this study. The dataset obtained through this study will enable to guide farmer`s decisions and extension planning for the development of seasonal water resource usage. Furthermore, this study will obtain information about water conserving effects on a well timed weeding strategy, the effects on soil moisture retention by tied-ridging and the potential of using decentralized water collection systems to provide life saving irrigation.

1.3 Intension and research questions

At slopes ranging from 3 % or more contour farming has positive impact on decreased surface run-off. Additional ridging improves water soil infiltration by creating a high degree of surface roughness (Hatibu and Mahoo, 1999). Surface structure as a water conservation possibility is often not included in models like AquaCrop (Vanuytrecht et al., 2014) or APSIM (Holzworth et al., 2014).

Tied ridges as a rainwater conservation technique, is a combination of ridge furrows, which are blocked with earth ties in a specific distance, forming micro-catchment basins in the field (Figure 2). Rainfall induced surface run-off is reduced by tied-ridging, but allows that dispensable water may drain off through the lower ties when the soil is already saturated. Do tied ridges affect water infiltration capacity and evaporation in terms of changed soil moisture characteristics?

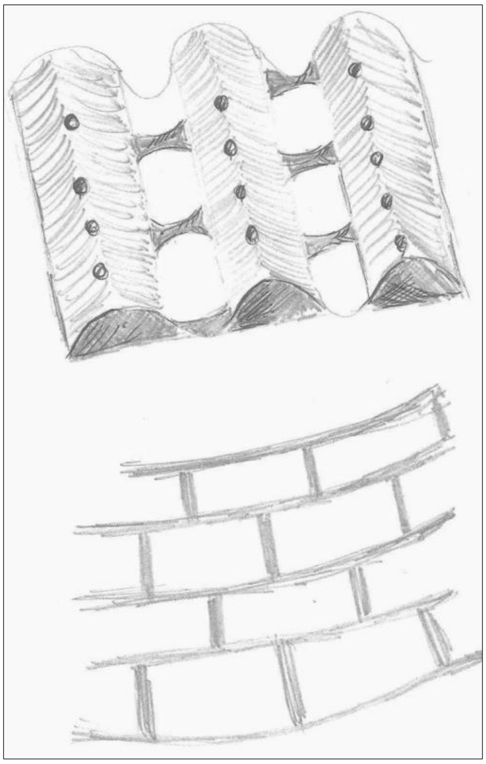


Figure 2: Tied-ridging system (above) and in connection with contour ridging (below) (in the style of Wiyo et al., 2000).

Hatibu and Mahoo (1999) described that contour farming and riding is no common practice in the Dodoma region. Farmers mentioned the lack of power, and equipment which are main reasons why farmers do not improve their water management. A driver for promoting this

practice would be a good implementation of ridging, resulting in increased yield and increased inducement to spend more effort in using contour farming and ridging.
Wiyo et al. (2000) described that the crop yield is affected by tied-ridging. But the grain yield variation depends mainly on the amount and distribution of rainfall, soil type and crop grown. Is tied-ridging an opportunity to use rainwater more efficiently by surface run-off reduction and could thereby contribute to feasibility of low-input rainfed upland rice production systems in semi-arid areas?

Water access and availability is often limited in semi-arid rural areas in SSA. Life saving irrigation is discussed as water saving opportunity with satisfying yields. Hereby soil moisture is monitored and soil moisture content kept above the permanent wilting point without fulfilling the crop water requirements. Is life saving irrigation a possibility to grow upland rice with adequate yields and reduced water input by irrigation? Is hereby tied-ridging an additional option to achieve even higher yields by reduced surface run-off during rain events?

In case of soil moisture conservation weed control is one of the most common agronomic practices in Dodoma region (Hatibu and Mahoo, 1999). By weeding two or three times, in contrast to a clean weeded alternative, the water loss will be monitored as soil moisture content deviation and microclimate measurements within the canopy. The effects of light and water availability in weed-crop interactions will be studied. Data obtained delivers information about the effect of evaporation vs. the water use of weeds. How does different minimal water management in combination with or without weeds vary soil water contents and competitions for light and water between weeds and crops? What are the effects of minimal water management in terms of tied-ridging and life saving irrigation on weed/crop density and crop yield?

In this study water conservation management practices in addition to a drip irrigation system obtain information about (minimal) water requirements for successful upland rice cropping and may improve decision support systems. Might there be an opportunity to decrease the risk of yield loss caused by extreme weather conditions like droughts or heavy rain falls or pest and diseases in terms of improved soil water characteristics? The potential of benefits and increasing income needs to be demonstrated and may lead to land and water conservation. Is there in that context an opportunity to enable cropping calendar planning and integration of upland rice into crop rotation practice? In conclusion, the main focus of this study is to evaluate the effects of minimal water management on the suitability to grow rice in seasonally drought prone areas in Tanzania.

2 Material and methods

2.1 Experimental setup

2.1.1 Location

The field trial was carried out at the Agricultural Research Institute (ARI) - Makutupora (05° 58.543´ S, 035° 46.118´ E) from January 2015 until May 2015 during the rainy season. The ARI research station belongs to the Mjini district of Dodoma, the capital of Tanzania. The field trials and the data collection for this master thesis were part of a PhD study. This PhD study collaborates which the German-Tanzanian framework within the GlobE project funded by BMBF (Bundesministerium für Bildung und Forschung) research project “Trans-SEC - Innovating Strategies to safeguard Food Security using Technology and Knowledge Transfer: A people-centered Approach”.

2.1.2 Treatments

To identify the effects on the performance of NERICA 4, 10 treatments were developed including minimal water management by modification of the soil surface, by adding a minimum amount of water and adapted weeding management.

1)	R + CW:	Rainfed + Clean weeding
2)	R + FW:	Rainfed + Farmer`s weeding
3)	TR + CW:	Tied ridges + Clean weeding
4)	TR + FW:	Tied ridges + Farmer`s weeding
5)	TR + LSI + CW:	Tied ridges + Life saving irrigation + Clean weeding
6)	TR + LSI + FW:	Tied ridges + Life saving irrigation + Farmer`s weeding
7)	LSI + CW:	Life saving irrigation + Clean weeding
8)	LSI + FW:	Life saving irrigation + Farmer`s weeding
9)	FI + CW:	Full irrigation + Clean weeding
10)	FI + FW:	Full irrigation + Farmer`s weeding

The treatments “rainfed (R)” and “full irrigation (FI)” were included to have a reference concerning on the one hand side the local rainfed conditions without any improvement or difference between the local rice growing practice and on the other hand side a treatment where all crop water requirements are fulfilled. We expected that the rainfed plots would have the lowest and the fully irrigated plots the highest soil water content. The FI plots always got enough water with the result that all crop water requirements were fulfilled. For further on information concerning the development of the irrigation schedule see chapter 2.2.

Regularly installed tied ridges (TR) along the contour lines prevented uncontrolled run off (see 2.1.3). By the size of the TR it was possible to regulate the amount of infiltrated water during a precipitation event. If the infiltration rate of the soil is exceeded, the TR allow run-off.
Life saving irrigation describes a method of irrigation where a minimum amount of water is added just to keep the soil moisture above the permanent wilting point to avoid plant stress. One stationary FDR sensor continuously monitored soil moisture under rainfed conditions. Additionally, soil moisture measurements were documented of all treatments twice a week (see Figure 14: placement of tubes). A rain gauge monitored rainfall.
The treatment with TR and life saving irrigation is a combination of those two treatments, mentioned above.

All these treatments were combined with two different weeding managements. Clean weeded plots were always free of weeds due to continuous weeding whenever it was necessary. Farmer`s weeding implemented that those plots were weeded three times within the growing period (for further information see: Weed and bird control 2.6.3).
Each treatment had four repetitions so the field trail contained 40 plots in total.

2.1.3 Tied ridges

Tied ridges are a specific change of the soil surface to improve water and soil conservation. It is a combination of regularly installed ridges along the contour lines of the terrain to avoid uncontrolled run-off, and ties in regular intervals which only allow surface run-off when the infiltration capacity of the soil is excited. Water retention and transmission properties of the soil are related to those processes and are mainly a result of the soil texture and soil composition (Nyamangara and Nyagumbo, 2010).

With more than 3 % slope, tied ridges can reduce soil loss up to 95 % (Germer et al., 2015) and 75 % run-off according to McHugh et al. (2007), who did his studies in semi-arid Ethiopia. The positive effects of tied ridges compared to flat planting or simple ridges are decreased run-off, increased water infiltration, and consequently greater water storage (Hulugalle, 1987). Hulugalle (1987) and

Araya and Stroosnijder (2010) are describing that plots with barley and tied ridges in northern Ethiopia gained yield compared to conventional flat ones.

The tied ridges were prepared by hand (Figure 3) and were directed perpendicular to the slope, which was 0.78 %. The ridges were 0.25 m wide and 0.8 - 1 m long. The ridges are 0.15 m in height and were linked at intervals of 2 m. Cross-ties are 0.1 - 0.12 m high.

Figure 3: Plot with tied ridges (TR) and LSI (left picture); and a rainfed plot with TR during 2nd renewing of TR (right picture).

2.1.4 Life saving irrigation

Life saving irrigation is discussed as water saving opportunity with satisfying yields. By adding a minimum amount of water the soil moisture is kept above the permanent wilting point.
Without water supply the water content in the soil is decreasing, because of root uptake and evaporation. During that process of decreasing water content the water is greater held by soil particles and the crop cannot extract water without energy effort. The wilting point is described as water content in the soil at which plants will permanently wilt, because the water uptake becomes zero (FAO, 1998).

FDR and TDR devices (2.5) monitored soil moisture and helped to decide if life saving irrigation was necessary. If soil moisture content reached the permanent wilting point (PWP) (additional information see 2.3) in addition to visible stress symptoms (Figure 4) of the crop, the treatment was irrigated. The LSI plots always got half the amount of water which was applied to FI treatments.

Figure 4: Non stressed and stressed rice plants; non stressed rice plants at LSI plot with soil moisture contents more than the PWP (left picture), two right pictures: rice plants at LSI plot with soil moisture contents less than the PWP with obvious stress systems in terms of leaf rolling.

The decision about irrigating the LSI plots was made in the morning before 9 am. Hereby plot specific soil moisture measurement and stress symptoms estimation of every plot with LSI were conducted. If 50 % of the leaves of one plant and 50 % of all plants within one plot show the stress symptoms of leaf rolling as illustrated in Figure 5, the plot was ranked as required to be irrigated according to the definition of life saving irrigation.

Figure 5: Demonstration of a rice plant without obvious water stress (left), and a rice plant with fully rolled leaves and obvious water stress (right).

2.1.5 Experimental field

The total experimental field trial at ARI was 75 m wide and had a length of 165 m. Within this field the plots with rice covered an area of 65 x 18 m. All plots measured 5.7 x 4.0 m covering a total area of 22.8 m^2. The plots and planting rows were arranged in east-west direction to minimize the effects of shading. Figure 6 illustrates how the treatments were arranged. According to the little slope in east-west direction the field was divided in four blocs based on the intensity of the slope and soil properties. Inside one block the treatments have been randomized. Every irrigated plot was connected with an irrigation pipe to the water pump. Valves allowed regulating the water supply according to the daily irrigation schedule.

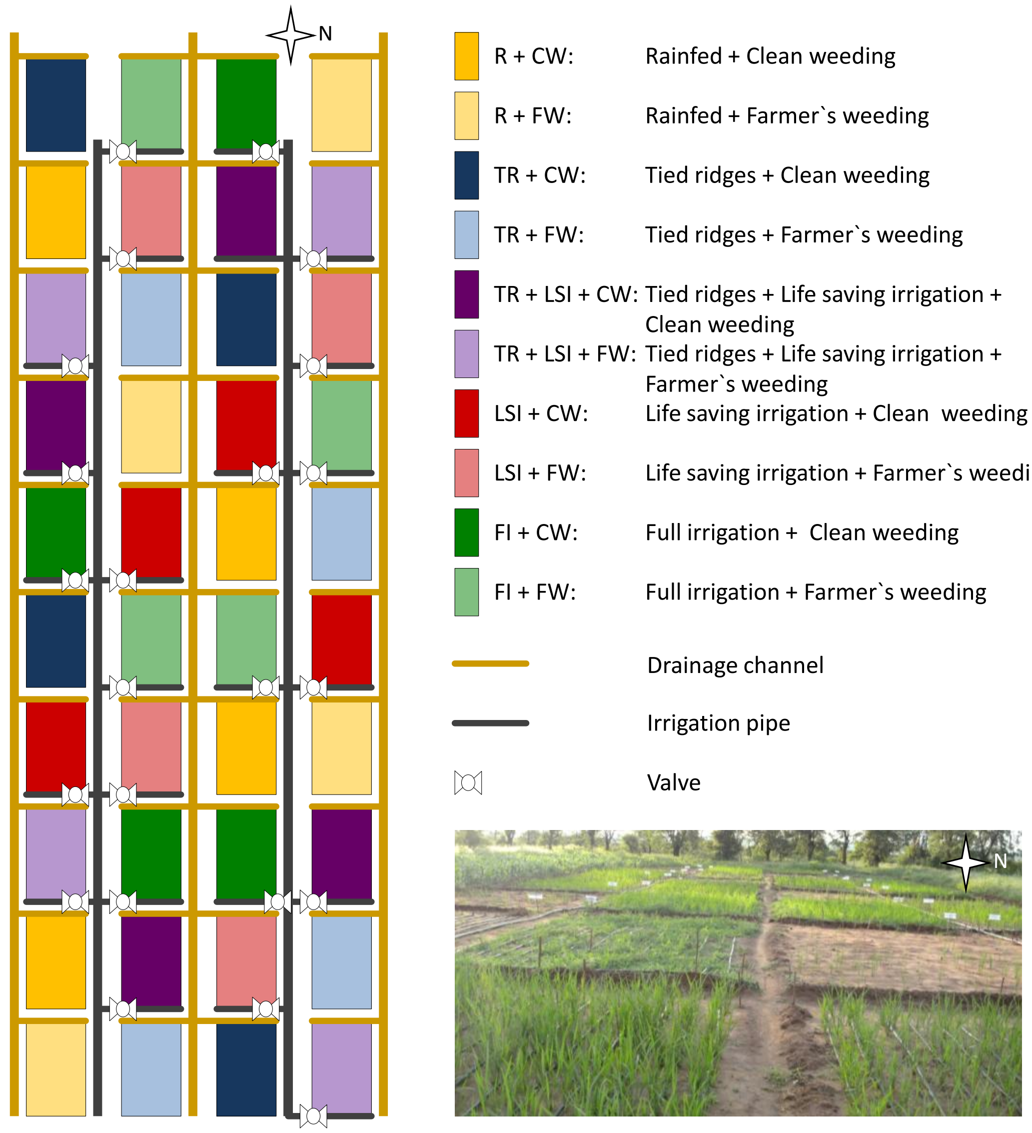


Figure 6: Randomized field layout, 10 treatments with 4 repetitions respectively.

Drainage channels were installed at the end of every plot (Figure 7) to collect surface water run-off to avoid that the run-off flows into the neighboring plot. Otherwise, due to the slope, the plots at a lower position would get more water during precipitation events. The surface water was channeled and leaded off the field.

Figure 7: Drainage channels.

2.2 Crop water requirements

This chapter is reflecting guidelines for computing crop water requirements and is related to the FAO Irrigation and Drainage Paper No. 56 (FAO,1998).

2.2.1 Crop evapotranspiration (ET_c)

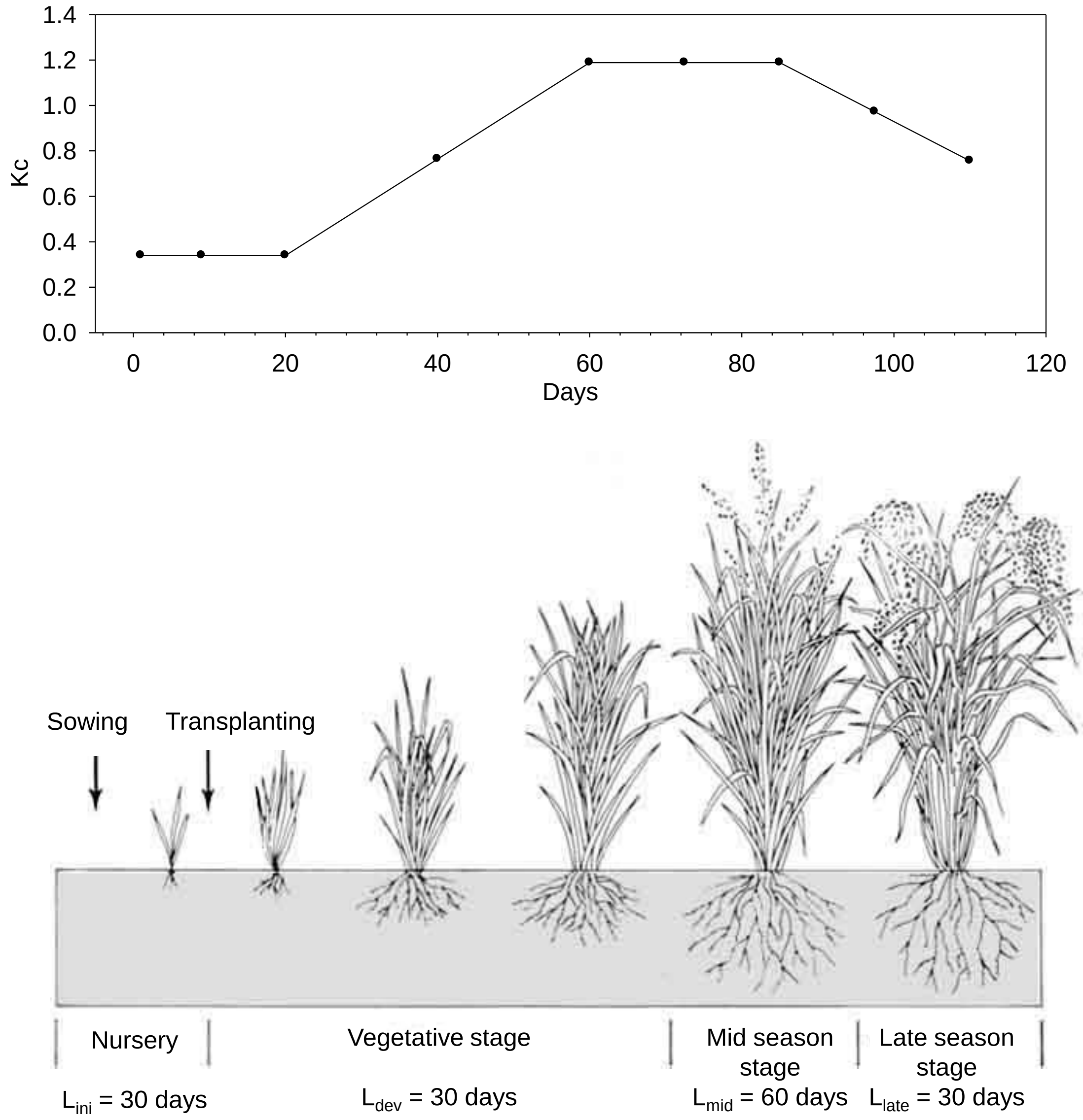
To identify the irrigation requirements several factors are essential. To calculate the crop water requirements (CWR) it is necessary to know the crop evapotranspiration (ET_c). The ET_c is calculated by multiplying the reference grass evapotranspiration (ET_o) with the crop coefficient (K_c) during the different growth stages.

$$ET_c = ET_o \times K_c \qquad (1)$$

Primarily the stage lengths of the crop need to be determined. The crop coefficient is divided into $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$. Crop transpiration and soil evaporation are included in the single crop coefficient. The K_c value is adjusted to the specific situation. The ET_o is based on long term climatic data (1980-2010) which is calculated on a ten day interval and was taken from the weather station of Dodoma airport. For detailed information about the ET_o per day which was taken for irrigation requirements see appendix 7.2.

2.2.2 Single crop coefficient (K_c)

The K_c factor includes the crop characteristics and the soil evaporation according to the different growth stages as shown in Figure 8. The crop growth stages are divided into four main stages, the initial or nursery, the development or vegetative stage, the mid-season or reproductive and the late or ripening stage. The K_c value includes crop characteristics like plant height, leaf area, ground coverage and effects of evaporation from the soil concerning different water management strategies. K_c values for the crop requirement calculation were taken from the crop coefficient curve in 10 day intervals (Figure 8, top).



Nursery:	From sowing to transplanting
Vegetative stage:	From transplanting to panicle initiation. Vegetative stage includes the tillering. Tillering means that several stems developed on one plant
	If the rice is sown directly (broadcast), the two stages combined are called the vegetative stage.
Mid season or reproductive stage:	From panicle initiation to flowering. This stage includes stem elongation, panicle extension and flowering. Late tillers may die.
Late season or ripening stage:	From flowering to full maturity. This stage includes grain growth.

Figure 8: Growth stages of rice (FAO, 1998, 1990) (The original figure and table had been modified), K_c diagram (top) is based on own data.

The single crop coefficient is integrating crop transpiration and soil evaporation. The $K_{c\ ini}$ is adjusted due to wetting frequencies of the soil surface. $K_{c\ mid}$, and $K_{c\ end}$ consider local climatic conditions.

$K_{c\ ini}$ value is obtained by FAO (Figure 9) should be multiplied by the fraction of soil surface wetted (f_w). In case of precipitation this value is 1.0 and for drip irrigation it varies between 0.3 - 0.4 (FAO, 1998). For partial wetting by irrigation the following formula is used to determine $K_{c\ ini}$.

$$K_{c\ ini} = f_w \times K_{c\ ini}\ (\text{Figure}) \tag{2}$$

According to Figure 9 $K_{c\ ini}$ has the same value for several crops. ET_c can be calculated on a daily basis as:

ET_o (January decade 3) (Table 12) = 5.7 mm/day

$K_{c\ ini}$ (Figure 9) = 0.99

f_w = 0.35

$K_{c\ ini}$ = 0.99 x 0.35 =0.3465

ET_c= 5.7 mm/day x 0.3565 = 2.03205 mm/day

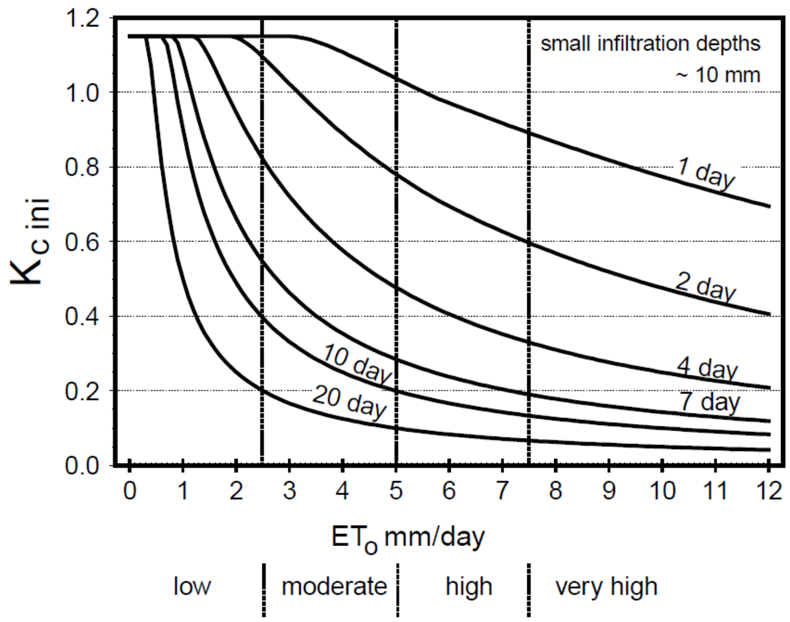


Figure 9: Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations and/or significant rain during the initial growth stage for all soil types when wetting events are light to medium (3 - 10 mm per event) (FAO, 1998).

$K_{c\ mid}$ and $K_{c\ end}$ are determined with 1.05 but need to be adjusted to the local climate conditions of Dodoma considering wind speed, humidity and plant height.

$$K_{c\ mid} = K_{c\ mid\ (Tab)} + [0.04\ (u_2 - 2) - 0.004\ (RH_{min} - 45)]\ (h/3)^{0.3} \quad (3)$$

Where:

$K_{c\ mid\ (Tab)}$ value of 1.05 from FAO table (FAO, 1998)

u_2 mean value for daily wind speed at 2 m height over grass during the mid-season growth stage [m s^{-1}], for 1 m $s^{-1} \leq u_2 \leq 6$ m s^{-1},

RH_{min} mean value for daily minimum relative humidity during the mid-season growth stage [%], for 20 % $\leq RH_{min} \leq$ 80 %,

h mean plant height during the mid-season stage [m] for 0.1 m < h < 10 m.

$K_{c\ end}$ is calculated as the $K_{c\ mid}$. The crop coefficient value for rice is 1.05, like for various agricultural crops growing under the same climatic conditions. Water management practices are reflected in $K_{c\ end}$. The value is relatively high if the crop is irrigated frequently until harvest or relatively low if the irrigation is less and has stopped earlier so the crop is allowed to reach senescence or to dry out on the field. According to the local harvest practice the $K_{c\ end}$ need to be adjusted.

$$K_{c\ end} = K_{c\ end\ (Tab)} + [0.04\ (u_2 - 2) - 0.004\ (RH_{min} - 45)]\ (h/3)^{0.3} \quad (4)$$

If the wind speed is greater or RH_{min} is higher, $K_{c\ end}$ increases. If the crop is allowed to dry on the field, wind speed and humidity have less effect on the crop coefficient and the $K_{c\ end}$ needs no adjustment.

To construct and describe a K_c curve the three values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$, which are adjusted to the local climatic conditions, are required. Furthermore the growing period needs to be divided into four growth stages as shown in Figure 8 and the K_c values, which corresponds to the different stages, need to be identified. Finally a straight line is constructed, connecting the straight horizontal line segments belonging to the initial ($K_{c\ ini}$) and mid-season ($K_{c\ mid}$) stage, and defining the course of the harvest management during the late season ($K_{c\ end}$) (Figure 8).

The crop coefficient can be calculated for any day during the growing period. The K_c values for the initial and the mid-season stage is constant, but varies between $K_{c\ ini}$ and $K_{c\ end,}$ during the growing period, and at the late season stage. Hereby the numerical determination of K_c is helpful.

$$K_{ci} = K_{c\ prev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right](K_{c\ net} - K_{c\ prev}) \quad (5)$$

Where:

i — day number within the growing season (1. length of the growing season),

$K_{c\,i}$ — crop coefficient on day i,

L_{stage} — length of the stage under consideration (days),

$\sum(L_{prev})$ — sum of the lengths of all previous stages (days).

It was not required to calculate the water requirement according to the duel crop coefficient and additionally would not have been possible because of a water requirement calculation on a daily base which needed to be done in the morning after soil moisture determination and before irrigation. The water access was cut at 11 am. Finally it was the lack of time which avoided using the duel crop coefficient.

2.2.3 Calculation of water supply and irrigation design

The weather data from the weather station from the airport in Dodoma (Tanzanian Meteorological Agency-TMA) from 1980 - 2010 provided the base for the calculation of ET_o. By importing that data to the ET_o calculator and using the software provided by the FAO the ET_o on base of the Penman Monteith equation was calculated. For decades of 10 days the average ET_o per day is used for further water supply calculations (for details about average ET_o during the growing season January - June see appendix 7.2).

ET_o x K_c = Et_c (mm/day)

ET_c + leaching requirement (15 % for example = 0.15 (Phocaides, 2000)) = Net irrigation requirement (mm/day)

Net irrigation requirement / irrigation efficiency (90 % for example = 0.9) = Gross irrigation requirement (mm/day)

Gross irrigation requirement x plant spacing (for rice 0.125 x 0.3 = 0.0375) x 2 hills = Gross irrigation requirement / 2 hills (mm/day))

(Gross irrigation requirement / 2 hills) / discharge rate (1 l/hour) = Duration of irrigation (hour)

(Gross irrigation requirement / 2 hills) / hour x 60 minutes = Duration of irrigation (minutes)

Table 2 is showing the crop water requirements of NERICA under the certain circumstances, resulting in Et_o values, adapted to the plant growth stages, related to the crop coefficient (K_c). Those two parameters are effecting the Et_c. As a result the CWR (crop water requirement) per irrigation is describing the amount of water which is applied within a specific period of time. For example the rice plants needed 12 mm of water within the first period which lasts 6 days to fulfill the CWR of the beginning of the initial stage.

Table 2: Crop water requirements (CWRs) of NERICA 4.

Irrigation no.	Days	Plant growth stage	Kc	Eto [mm/day]	Etc [mm/day]	CWR per irrigation [mm]
1	6	Initial	0.3	5.9	2.0	12.0
2	10		0.3	5.6	1.9	19.1
3	5		0.3	5.7	1.9	9.7
4	7	Development	0.5	5.7	2.6	18.1
5	3		0.5	5.7	2.6	7.8
6	6		0.7	5.7	3.8	22.7
7	4		0.7	5.4	3.6	14.4
8	6		0.9	5.4	4.8	28.5
9	4		0.9	6.0	5.3	21.2
10	5		1.1	6.0	6.3	31.3
11	4		1.1	6.1	6.7	26.7
12	5	Medium	1.2	6.1	7.3	36.5
13	10		1.2	6.1	7.3	72.8
14	11		1.2	5.8	6.9	76.1
15	10	End	1.1	6.1	6.7	67.3
16	10		0.9	5.8	5.1	51.4
17	4		0.9	6.0	5.3	21.2
18	7		0.8	6.0	4.6	31.9
19	6		0.8	5.8	4.4	26.5

According to the CWR values and the total rainfall of the growing season 2015, the amount of water applied by irrigation was adapted. Furthermore Table 3 is showing the amount of water which was needed at flat treatments and at treatments with tied-riding when run-off can be avoided. The irrigation number is similar to the number in Table 2 according to the crop coefficient and Et_o values. Additionally the total amount of water which was irrigated at FI and LSI treatments is shown. The actually amount of water applied is higher than the amount of water needed because of the leaching fraction and the irrigation efficiency.

Table 3: Adaption of supplemental irrigation (SI) in mm in the cropping season 2015 for treatments with total crop requirement fulfillment (FI), tied-ridging (TR) and life saving irrigation (LSI).

No.	CWR [mm]	Total rainfall [mm]	Run-off [mm]	SI water needed [mm] flat	SI water needed [mm] TR	FI water applied [mm]	LSI water applied [mm]
1	12.0	49.2	12.0	-37.2	-25.2	0.0	0.0
2	19.1	5.0	0.0	14.1	14.0	14.0	9.1
3	9.7	15.8	4.0	-6.2	-2.2	10.3	8.3
4	18.1	7.4	1.0	10.7	11.6	22.0	3.1
5	7.8	29.6	7.5	-21.8	-14.3	10.6	3.7
6	22.7	0.0	0.0	22.7	22.7	23.4	15.1
7	14.4	0.0	0.0	14.4	14.4	15.0	7.5
8	28.5	31.4	6.3	-2.9	3.4	15.5	7.8
9	21.2	0.0	0.0	21.2	21.2	20.7	3.7
10	31.3	41.8	12.2	-10.6	1.6	26.7	3.4
11	26.7	8.0	1.2	18.7	19.9	7.4	3.7
12	36.5	2.8	0.0	33.7	33.7	38.2	9.4
13	72.8	0.0	0.0	72.8	72.8	82.2	35.7
14	76.1	16.2	3.2	59.9	63.2	77.0	31.5
15	67.3	42.8	10.7	24.5	35.2	35.0	7.0
16	51.4	2.0	0.0	49.4	49.4	49.3	16.8
17	21.2	0.0	0.0	21.2	21.2	21.8	10.9
18	31.9	41.0	13.7	-9.2	4.6	30.2	11.5
19	26.5	1.2	0.0	25.3	25.3	9.2	4.6
Total	594.9	294.2	71.7	300.7	372.5	508.5	192.7

The water is supplied through a drip irrigation system (Figure 10). According to the crop requirements and the available equipment the 22.8 m^2 big plots were provided with 15 drip lines with 18 emitters (distance between emitters: 30 cm, flow rate/dripper: 1.0 l/hour, inlet pressure 1.6 bar) at one drip line. Every plot had its specific valve which contributed to selective irrigation of fully irrigated and plots with LSI.

Figure 10: Drip irrigation system.

The drip lines were installed between alternate rows which resulted in one emitter supplying water to two hills (plant spacing within the row: 30 cm, row spacing: 12.5 cm).

The FI treatments always got the amount of water to fulfill the crop water requirements. The schedule was adapted to the daily rainfall and irrigation skipped if the amount of rainfall exceeded the water demand. If the LSI requirements were fulfilled (see 2.1.4) the LSI treatments got half of the amount the FI treatments got.

2.3 Soil

Soil type and soil characteristics are playing a major role concerning nutrient supply and water balance and defining the key parameters which are limiting plant development. The soil type, where our field trial was conducted, was a Rhodic Cambisol. According to the WRB (World Reference Base) and FAO-system, Rhodic Cambisol is also named Terra fusca and characterized as a soil out of carbonate and gypsum rock which is typically clay rich, plastically and dense. Figure 11 is showing the soil composition, differing between sand, silt and clay fractions. A bulk density of 1.38 g cm^{-3} was measured. Chemical characteristics are shown in Table 4.

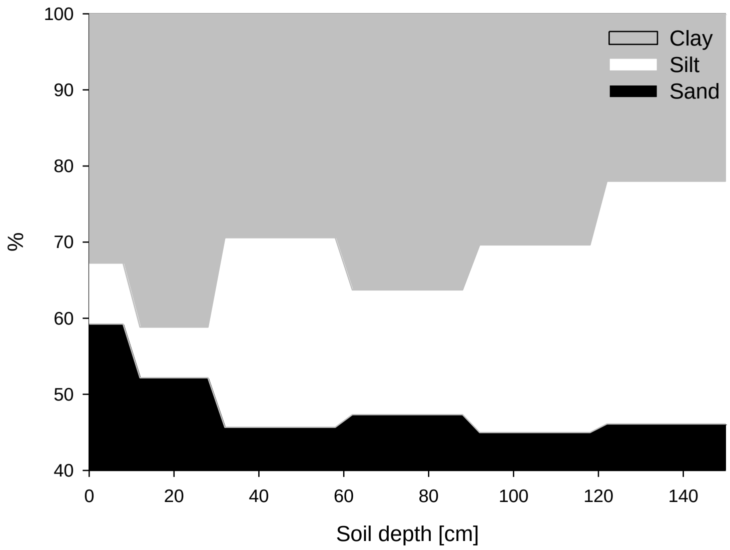


Figure 11: Soil composition of the soil at our field trial.

The amount of organic N in 0 - 30, 30 - 60 and 60 - 90 cm depths is 0.05, 0.04 and 0.03 % respectively. The amount of organic C in 0 - 30, 30 - 60 and 60 - 90 cm depths is 0.42, 0.29 and 0.24 % respectively.

Table 4: Chemical characteristics of the soil at our field trial.

	Na	**Ca**	**Mg**	**P**	**K**	**pH**	**Electrical conductivity**	**KAKpot**
Unit	mmol/kg	mmol/kg	mmol/kg	mg/kg	mg/kg		µS	mmolc+/kg
0 - 10	0.3	44.5	18.2	16.7	413.7	7.0	58.4	106.5
10 - 30	1.2	44.6	18.5	5.2	295.2	6.6	61.3	116.3
30 - 60	3.2	41.4	25.2	2.5	472.3	7.6	55.3	124.1
60 - 90	2.0	46.8	22.1	5.0	621.8	7.5	59.0	131.4
90 - 120	5.0	45.2	26.7	1.4	204.2	6.6	101.2	125.8
120 - 150	6.3	64.3	30.7	1.3	133.3	7.0	87.0	154.8

To evaluate the hydrologic balance of soil parameters like field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC) were introduced. The FC is defined as the water which soil can hold against the force of the gravity. The FC depends on the soil water equilibrium, the profile depth, the amount of organic matter, texture and the arrangement of the horizons (Horn et al., 2010).

Additionally to the FC values delivered by literature, according to different texture compositions, the FC of the soil at the field trial was determined with a simple experimental set-up. Hereby 12 soil samples were taken in different depths (10, 20, 30 and 30 - 60 cm with three repetitions), which then were placed in a bowl with sand and water, until the samples were saturated (Figure 12). The total weights of the soaked samples were determined.

Figure 12: Soil samples were soaked in water until saturation for FC determination.

Afterwards the samples were placed on a filter on top of a ceramic plate. This setup was lifted up to a height of 63 cm above the water level in the vessel on the bottom collecting surplus water. 63 cm water column (WC) correlates to a pF-value of 1.8 (1 cm WC = 0.98 mbar roughly 1 mbar = 10^2 Pa = 1 hPa). The ceramic plate is connected with a tube conducting water into the vessel. The system should not lose water by evaporation. All the water which cannot be hold in the system against the gravity was taken out of the system. When there is no more water flowing down into the vessel, the soil reached the FC. The amount of water corresponding to the FC is determined by weighing the samples at FC, putting them in the drying oven until all water is removed, weigh them again and calculate the difference. The Rhodic Cambisol at our field trial reached an average FC of 28 %.

The permanent wilting point (PWP) is describing the situation when the plant cannot take up water from the soil anymore. Through transpiration the plant loses water and the soil is not delivering water to the plant anymore. As a result the plant is wilting. This soil characteristic was a key parameter for modeling our irrigation schedule for the plots with life saving irrigation. The PWP is calculated by dividing the FC by 1.85 for medium texture (FAO) according to the bulk density of 1.38 g/m^3. The soil at our field trial had an average PWP of 15.2, 13.7, 15.3, 15.2 and 16.5 % respectively to the soil depths of 10, 20, 30 and 30 - 60 cm.

The water capacity (AWC) is describing the amount of water in the soil to prevent leaching and to avoid water stress for the crop. This range is defined by the difference between the field capacity (FC) and the permanent wilting point (PWP).

$$AWC\ (\%) = FC\ (\%) - PWP\ (\%) \tag{6}$$

The soil at the field trial had an average AWC of 12.9 %.

2.4 Climate

Climate data from the Dodoma airport from 1980 to 2010 was used to create the irrigation schedule for the irrigated treatments. Unfortunately no long term climate data from the ARI-Station was available. Since the beginning of the big field trail in 2014 a DELTA-T automatic weather station (WS-GP2) was installed right next to the field, logging temperature, humidity, rainfall, wind speed and direction; parameters necessary to adjust crop water requirements (2.2) of the rice plants.

Table 5 is showing the long term rainfall characteristics from 1980 until 2010 in Dodoma. The mean amount of rainfall in that area is 429.4 mm for the growing season; meaning from January until May. This amount of water is mainly distributed from January until March where the average precipitation is more than 100 mm per month. Traditionally the farmers establish their crops at the beginning of the year. Crops with a growing period between 120 - 150 days are reasonable to be chosen. Thus the crops reach maturity at the end of April/beginning of May, when precipitation is less than 10 mm per month.

Table 5: Summary of long term (1980-2010) rainfall characteristics for Dodoma (Dodoma airport) and the rainfall pattern for the growing season 2015.

Month		Jan	Feb	Mar	Apr	May	**Season**
Long term Rainfall [mm]	Mean	136.4	120.2	116.9	51.2	4.7	**429.4**
2015 Rainfall [mm]		111.8	201.8	27.0	85.8	1.4	**328.8**

With the field specific weather station it was possible to have detailed climate information concerning the plant development at the field trial. Measurements of daily rainfall helped to adapt the irrigation schedule to the actual water supply. Figure 13 is showing the climate data which was collected next to the field trial. The amount of rain from January - May was 328.8 in total separated into 111.8, 102.8, 27, 85.8 and 1.4 mm respectively (including December with 47 mm as water supplier for germination, 375.8 mm in total).

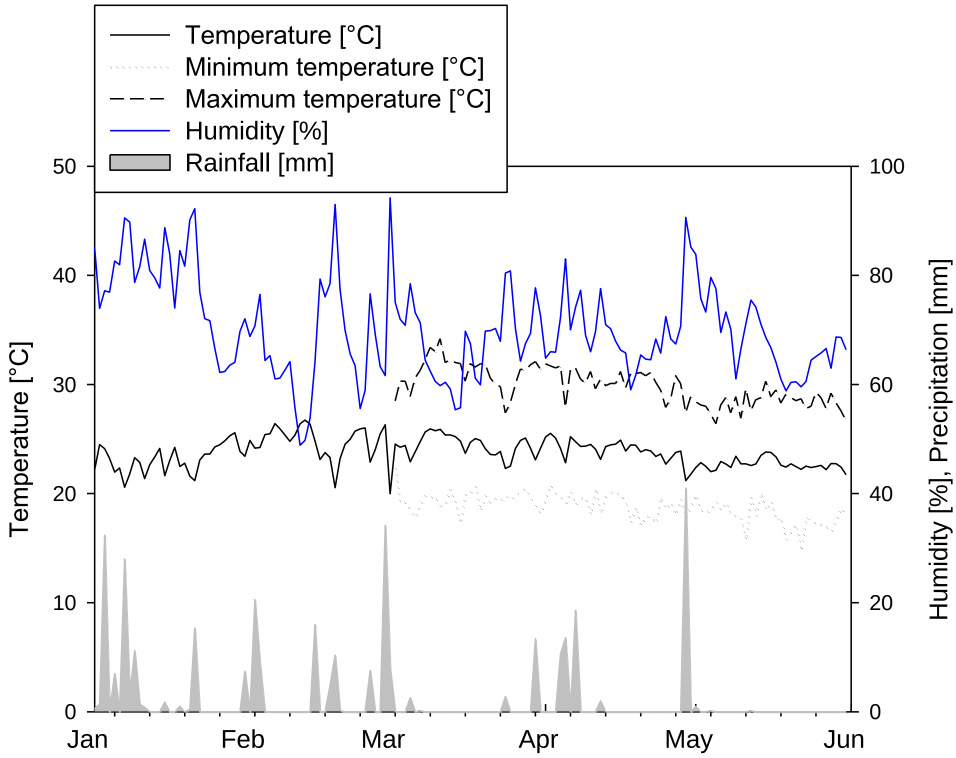


Figure 13: Climate data from the weather station next to the field trial.

To calibrate the data from the weather station one Tinytag (Tinytag Plus 2 Data Loggers) was running next to that weather station. Two Tinytags, which are recommended to measure temperature and humidity in a variety of harsh and outdoor application, were installed inside of the rice canopy to measure the microclimate (Tinytag from Gemini Data Loggers, 2015). To determine a possible influence of weeding on the microclimate of the plots, we installed one Tinytag, swinging freely 10 cm above the soil in a plot with full irrigation with farmer`s weeding and one in a FI and clean weeded plot. Additionally one Tinytag per plot in the above mentioned two treatments measured the soil surface temperature.

2.5 Soil moisture

To investigate the soil moisture, according to the different treatments, soil moisture tubes were inserted in three repetitions per treatment (Figure 14 left picture right tube, Figure 14 left picture middle tube). The PR2 probe (Profile Probe; Delta-T Devices Ltd., UK) is a FDR- (frequency domain reflectometry) device to measure the soil moisture by sending electromagnetic fields into the soil. With the four sensors along the probe it is possible to detect the soil moisture in 10, 20, 30 and 40 cm depths (Figure 14, right probe with 50 cm length). For the collection of soil surface moisture data of the surface a TDR-

(time domain reflectometry) device was used (Figure 15). The SM300 soil moisture sensor (Delta-T Devices Ltd., UK) was inserted right next to the soil moisture tubes for the PR2 probe and delivered data about the water content up to 5 cm depth. The measured soil moisture in 5 depth was also used for the suggestion about irrigating the LSI plots.

Figure 14: Soil moisture tubes for the PR2 probe in a treatment with life saving irrigation and tied ridges (left picture) and at a plot without tied ridges.

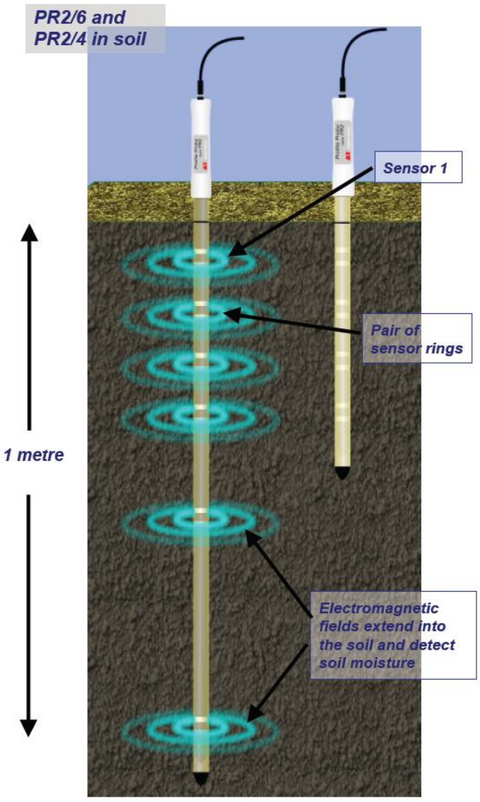


Figure 15: PR2-FDR soil moisture probe (Nicholl, 2004) (left); SM300 surface TDR soil moisture measuring device (SM300 Soil Moisture Sensor, Soil Moisture Measurement) (top).

To achieve specific accuracy of our soil moisture measurements the soil moisture data needed to be adjusted by calibrating the SM300 and the PR2 probe. Hereby soil samples were taken next to the soil moisture tubes according to the sensors depths of the SM300 and the PR2 probe in 5, 10, 20, 30, and 40 cm depths with three replications as shown in Figure 16. The density of the samples shouldn`t be changed (Nicholl, 2004). By taking samples according to the named depths at four times with different soil moisture contents (by adding water into the system) the deviation should be reduced.

Figure 16: Soil moisture device calibration; left picture: Taking soil samples next to the soil moisture tube of the PR2 probe; right picture: taking soil samples four times (five depths) with different soil moisture contents.

The samples were weighed before and after drying. The samples need to dry in the drying oven above 105 °C for several days to garantee that all available water is evaporated. The difference of weight between the wet and the dry sample is resulting in the amout of water which is gone and in the amount of water which was measured at the time of soil moisture measurement at the field by the two different devices.

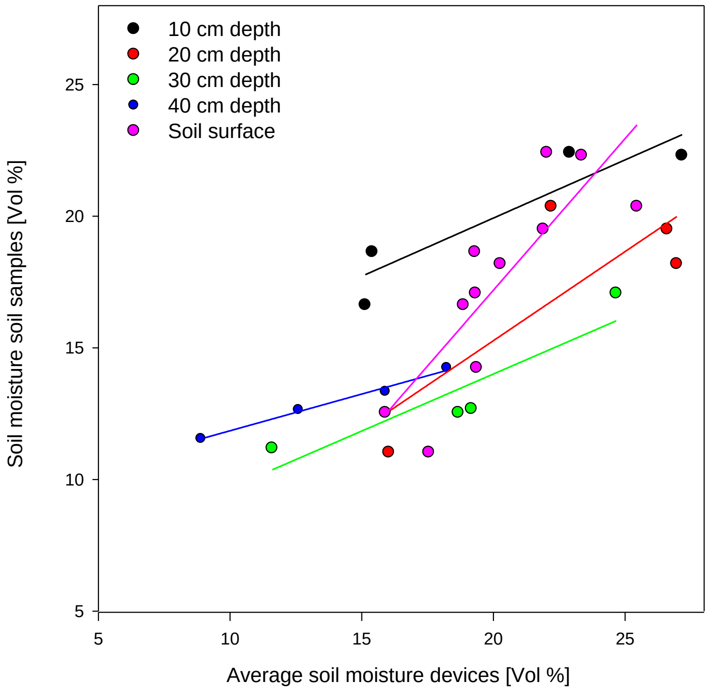


Figure 17: Calibration of soil surface TDR-device (SM300) and FDR-device (PR2) in four different depths.

By using a scatter plot with regression (Figure 17), the data was delivering regression functions which were used to adjust the soil moisture data collected for this study. The following fuctions were used:

Soil surface (SM300):	$y = 1.1509x - 5.8274$
All depths (PR2):	$y = 0.5214x + 6.0479$
10 cm (PR2):	$y = 0.442x + 11.091$
20 cm (PR2):	$y = 0.6766x + 1.742$
30 cm (PR2):	$y = 0.4332x + 5.3435$
40 cm (PR2):	$y = 0.2787x + 9.0649$

The soil moisture measured during the growing season of 2015 is shown in Figure 18. The PR2 probe was stationary inserted next to the weather station and deliverd soil moisture data in a frequency of 10 minutes. The diagramm above in Figure 18 is showing the change of soil moisture according to the rainfall events seperated into soil moisture contents at four different depths. The average soil moisture content is shown in the diagramm below where one should also follow the moistening and the drying of the soil adapted to the water intake into the system by rain.

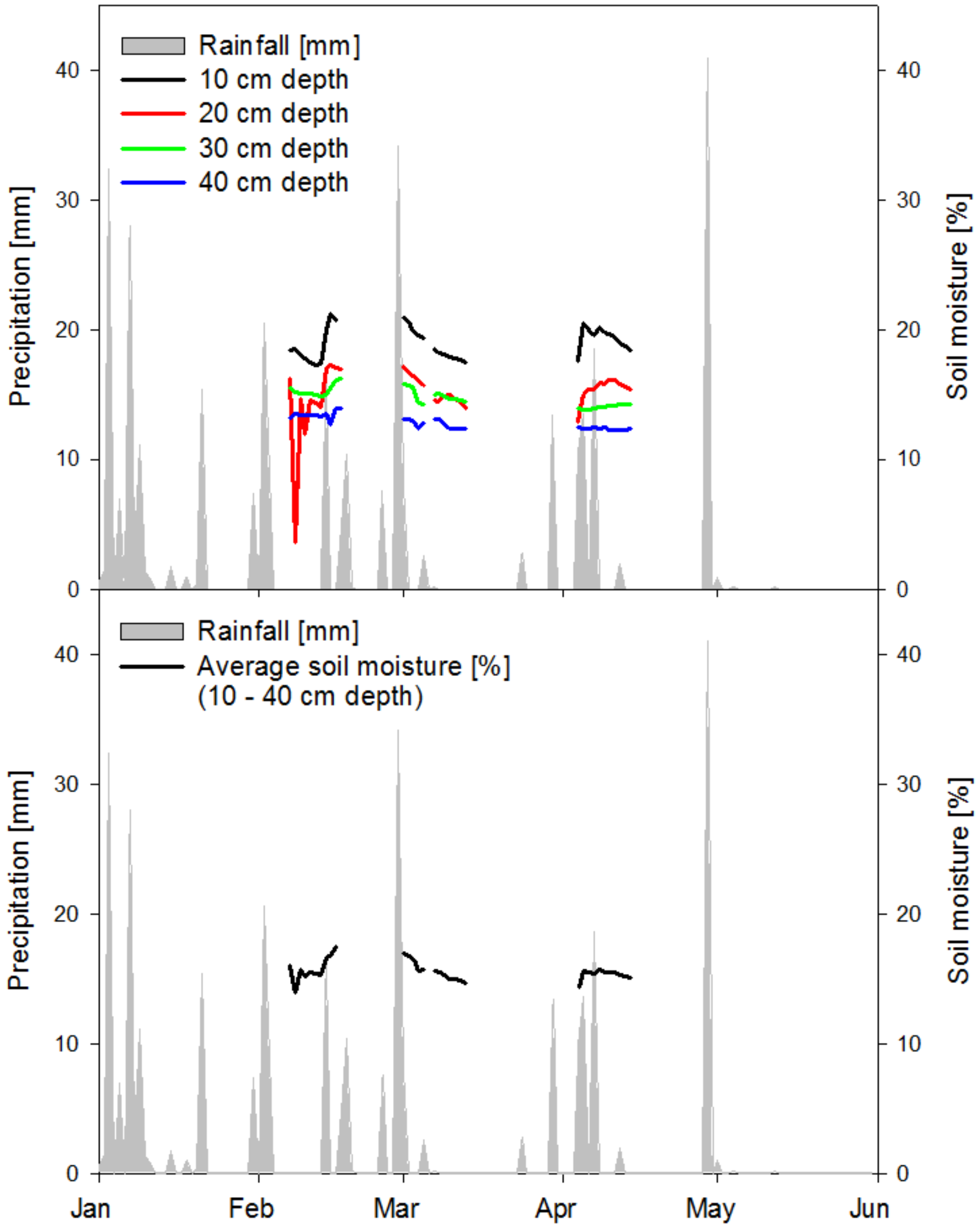


Figure 18: Soil moisture contents during the growing season of 2015. Installation of the PR2 device next to the weather station, logging every 10 minutes.

2.6 Crop management

2.6.1 Germination test

By seed selection it is possible to select viable seeds which are probably more germinable. The seeds were put in water until they were soaked with water. The floating seeds have a lower germination rate and the sunken ones are viable seeds. By separating those it is possible to get a higher germination rate in the field by a cheap and easy method.

For the germination test the floating method on a small scale was used for seed selection. After counting 3 three times 100 seeds I wrapped them in wet paper, put them in a plastic bag and stored the three probes in a dark place. Daily I checked the germination rate to follow the development of emergence. After 5 days the first germinated seeds were counted. After three weeks the test was stopped because the number of germinated seeds was not increasing anymore. The average number of counted germinated seeds in the three bags was 33.3 %. According to Food Crop Diversification Support Project (2010) seeds with a germination rate with more than 80 % should be chosen.

2.6.2 Sowing

Figure 19: Sowing with farmer`s practice (4/1/2015).

All fieldwork was done manually except of the ploughing at the very beginning of the field preparation. With the dibble method the rice was sown on the 4/1/2015. The time of sowing was chosen because of the local practice and the first precipitation events after the dry season. According to the Food Crop Diversification Support Project (2010) 7 seeds per hill were deposited (distance 12.5 x 30 cm, see Figure 20). This results in an average of 50 kg/ha. With farmer`s practice the hills and the rice seeds were deposited by hand. The seed depth was 2 - 3 cm (Food Crop Diversification Support Project, 2010).

Because of the low germination rate (see 2.6.1) and the low precipitation (see Table 5) in January during germination/emergence we transplanted rice plants from hills with more than 2 plants, to hills with less or without plants (at 11 days after sowing over a period of 18 days from the 30/1/2015 until the 16/2/2015). At the sowing date we installed a backup with additional rice seeds/plants to minimize the risk of too less rice plants. Never the less the decision was made to abandon 5 plots to fill up the other plots.

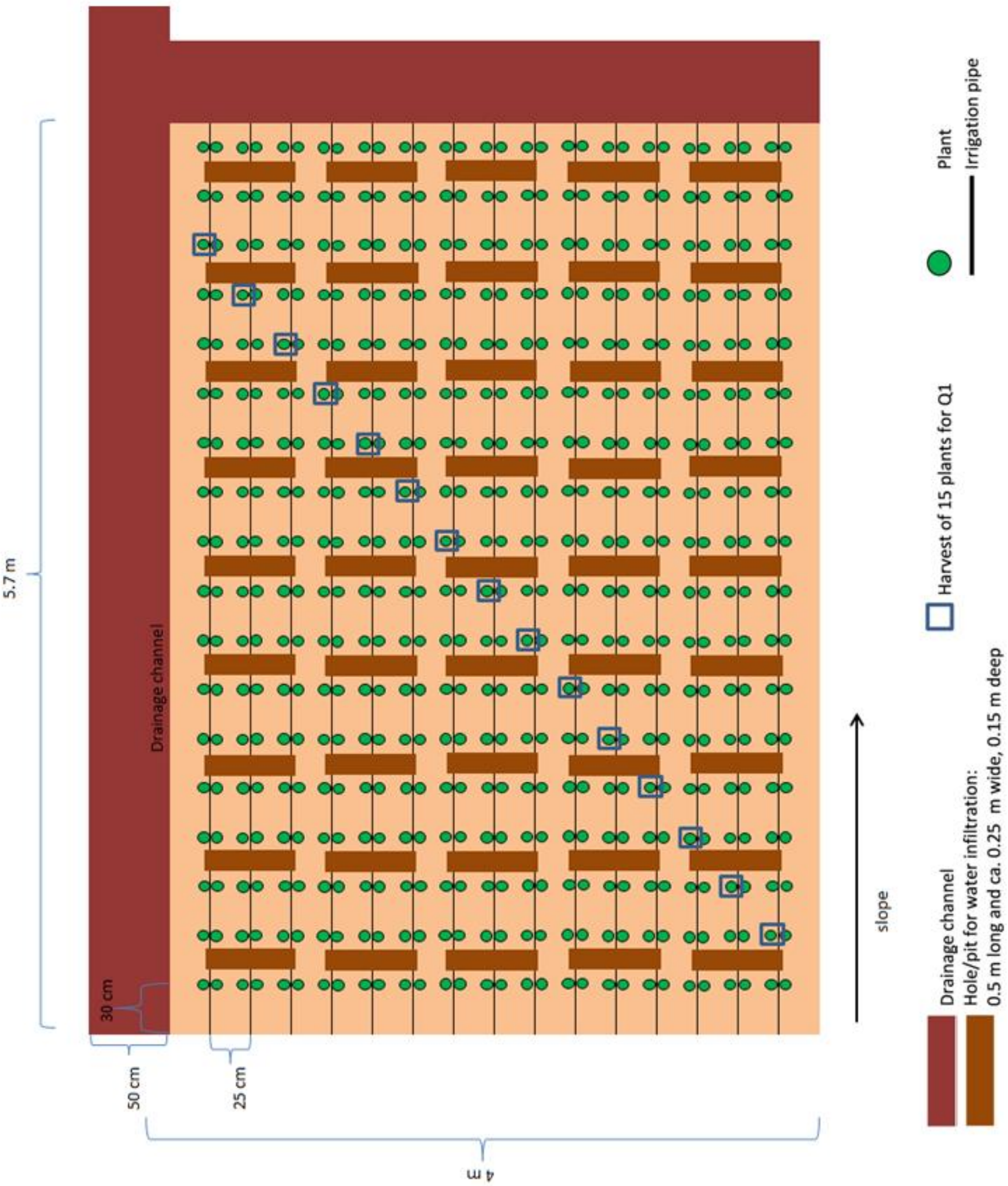


Figure 20: Plot layout; Q1: 15 plants which were harvested for HI.

According to Makutupora station practice (MSP) 60 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1} via Yara Mila complex fertilizer (23 - 10 - 5), Potassium Nitrate (13 - 0 - 46), Triple Super Phosphate (0 - 44.5 - 0) and Urea (46 - 0 - 0) were applied to the rice plots (Table 6). Yara Mila, Potassium Nitrate and TSP (Triple Super Phosphate) were added into each hole at sowing (basal dressing). Additional top dressing fertilizer (Urea) was applied during the growing period at the 06/2/2015 according to the recommended practice of 4 - 6 weeks after emergence.

Table 6: Applied fertilizer.

Type of fertilizer	Time of application	Application (kg/ha)	N (kg)	P_2O_5 (kg)	K_2O_5 (kg)
Yara Mila Complex (23 - 10 - 5)	At sowing	200.0	46	20	10
Potassium nitrate (13 - 0 - 46)	At sowing	43.5	6	0	20
TSP (0 - 44.5 - 0)	At sowing	22.5	0	10	0
Urea (46 - 0 - 0)	4 - 6 weeks after emergence	18.2	8	0	0
Total nutrient supply			60	30	30

2.6.3 Weed and bird control

Two types of weed control were used according to the 10 treatments. Five treatments belonged to the clean weeding method, 5 to the farmer`s practice method. The clean weeding method implicated weed free plots at all growing stages. Weed control was done at all clean weeded plots simultaneously and frequently often.

The farmer`s practice included three dates of weed control: First during germination/emergence (9 - 12/1/2015), second after emergence (22 - 24/1/2015) and the last time at canopy closure (9 - 10/3/2015) (Figure 21). Weeding rice is quite labor intensive and it took us always two or three days to finish weeding.

Figure 21: Manual weeding 63 DAS at a FI plot (right); left: unweeded LSI plot with weed density estimation frame.

To estimate the effects of weeds on the productivity of a plot it was important to include the weeds biomass production at the plots with farmer`s weeding.

Therefore the weeds which were removed at canopy closure were collected in bags to get the fresh weight of weeds per plot. To get the dry weight three subsamples a 100 g were taken randomly. They were dried in the drying oven and weighed again afterwards. This procedure was conducted at weeding at canopy closure and again at the 16/5/2015 after the final harvest.
Additionally weed and crop density were estimated 56 and 140 DAS (days after sowing) by a frame covering one m^2 including 16 hills.

The experience of the farmers had shown that bird control is necessary to avoid yield loss. Especially at the end of the rainy season the grain attracts birds and other animals which could damage the whole field or only some plots which are not comparable anymore to undestroyed ones. The research field was occupied, during germination and from grain filling until harvest by manual bird protection from sunrise until sunset.

2.7 Measurements during the growing period

In addition to parameters determining yield components, described more detailed in the next chapters, the general status of the plots was observed. The number of plants per plot was counted and the yield loss visible as White heads was estimated by counting the amount of panicles per row, the number of White heads and the number of unfilled spikelets.

2.7.1 Determination of phenological stage

According to the BBCH-Scale the development of the rice plants was determined every two weeks to monitor how the plants behaved at the different treatments. Hereby one plant per plot was chosen randomly; plant height and diameter were measured, number of leaves and tillers counted and the present respectively the emergence of heads was noted.

2.7.2 Destructive harvest during growing period

Two times during the growing period three rice plants per treatment were harvested to determine the specific plant development. Hereby the plot was divided into four quarters - image the plot is half split lengthwise and breadthways. At the first harvest on the 23/2/2015 a plant from the middle of the first quarter were taken. The second quarter delivered the plant for the second harvest on the 28/3/2015. If one of those plants was missing, a plant from one of the other two quarters was taken. The dates of the destructive harvests were chosen to determine the individual plant development according to their water availability in the vegetative and the generative phase.

Before cutting the chosen plants several plant parameters were taken. Length and width were measured and the number of tillers was counted. Additionally at the 2nd harvest during the generative phase the number of heads and their development were noted.

After cutting the plants at the 1st destructive harvest we separated the stem from the leaves measured length and width of the leaves for LAI determination and put them separately in paperenvelopes. At the 2nd harvest length and width of the leaves were also measured, but additionally the leaves and the tillers were scanned and the heads were separated from the stem if available. The samples also went into paperenvelopes and were put in the drying oven at 75°C until a constant weight was reached. Further on the dry samples were weighed.

2.7.3 Leaf area index (LAI), specific leaf area (SLA)

LAI is the leaf area per unit ground area (m^2/m^2). The rice canopy can be described by this dimensionless quantity. This parameter may provide information about the estimated amount of water loss by evapotranspiration due to canopy water interception, the microclimate and does additionally provide information about yield development. Plants adapt their productivity to any change in canopy leaf area index (Bréda, 2003). Bréda (2003) is calling LAI as one of the most difficult to quantify quantity because of the spatial and temporal variability, also because of heterogeneity, stratification, annual cycles and interannual variability, which lead to changing stand or crop stand. Several methods have been developed to measure LAI, but it is difficult to quantify the most appropriate method according to a specific situation, object of interest, required accuracy, the time of measurement, the research scale, and the available budget.

LAI at our field trial was measured by LAI2000 (LI-COR, Lincoln, Nebraska, USA) every second week starting from the 46th day after sowing (DAS). To have a reference LAI we did two destructive measurements. At the first destructive harvest it was not possible to scan the leaves which was our original plan. Just after cutting the plants the leaves rolled completely. Therefore we measured length and width of the leaves and determined the LAI by a corresponding formula. At the second destructive harvest we scanned the leaves, the stems, and the panicles separately. The LAI was finally determined by the help of a picture processing software. Additionally we measured length and width of the leaves again as at the first destructive harvest.

2.7.3.1 Indirect method: LAI2000

The amount of radiation which is passing through the canopy delivers information about the thickness of foliage and leaf orientation. LAI2000 utilizes this fact to measure LAI by the use of a “Fisheye” lens with hemispheric field-of-view (Figure 22, left picture). Five zenith angels allow the measurement of diffuse sky radiation from 0° to 74°. LAI2000 is ideally used under overcast sky. By the use of LAI2000 under sunny condition the LAI can be underestimated. Therefore we always measured in the late afternoon. The sun angel and the leaf angel distribution may force the underestimation up to 10%.

The interception of blue light by comparing measurements above (A values) and below (B value) the canopy is measured by LAI2000 to calculate LAI. The A readings should be made right before the B readings to avoid that changing sky conditions adulterate the real LAI. The sensors are measuring any light-blocking-object without differing between leafs, stems or any other non-natural object. Under different light conditions the use of 45° restricting cap (Figure 22, right picture) is necessary to avoid that irrelevant object like the person who is measuring, is influencing the measurement of LAI (LI-COR, 1992).

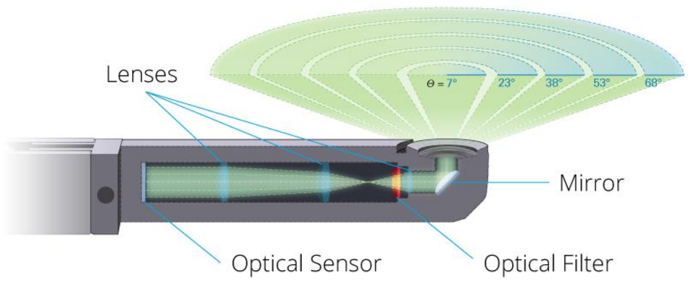


Figure 22: “Fisheye” lens with hemispheric field-of-view of LAI2000 (left), View restricting cap 45° (right) (LI-COR, 1992).

LAI was measured with LAI2000 6 times, starting from the middle of February at intervals of around 2 weeks until the middle of April. To see the effect of weeding on the LAI I measured before and after weeding at canopy closure (9 - 10/3/2015). The recommended adjustment of an ABBBB ABBBB measurement was chosen. The data was downloaded and organized by the FV2200 2.0 Software.

2.7.3.2 Direct method: Scanning leaves for LAI

A combination of scanning and image processing of cut rice plants provided one method for direct determined LAI. This method of scanning leaves and processing images was only used at the second destructive harvest. A maximum of three plants was harvested, put in ice cold water and scanned as soon as possible to avoid the rolling of the rice leaves. One plant for each clean weeded plot was scanned. To scan one plant from each of the 35 plots was not possible, because the harvested plants needed to be processed just after harvesting; more plants did not fit into the time frame. At the first destructive harvest it was not possible to have the leaves scanned before they rolled.

Leaves, stems and heads were scanned separately with a common scanner (and software: HP Kopierprogramm (SJ300)). By the following instructions it was possible to get the LAI with the knowledge of the amount of pixel of the scans by using the GIMP 2 (GNU Image Manipulation Program) program. The scans needed to be saved as *.jpg (Figure 23, left picture). By changing the settings of brightness to -80 and the contrast to 120 (Figure 23, middle picture) and select the dark objects afterwards, the amount of pixels per scan is shown. For example at Figure 23 LAI can be calculated as follows: the marked objects have 552661 pixels (Figure 23, right picture); the scanned picture in total has 3973320 pixels; 1 cm² has 6226.1 pixels. Divide the amount of detected pixels from the marked objects with the amount of pixels per 1 cm²: 552661/6226.1 = 88.8 cm². Accordingly the leaf area of the scanned leaves is 88.8 cm². Furthermore the leaf area of one rice plant needed to be adjusted to the leaf area per m^2, according to the plot specific rice plant density, to estimate the LAI.

Figure 23: Processing of scanned leaves with GIMP 2 to get a destructive measured LAI; left: initial unprocessed leaf scan, middle: changing brightness and contrast and detect black objects, right: amount of pixels for the detected objects which is used to calculate LAI for the scanned leaves.

2.7.3.3 Measuring length and width for LAI

Measuring length and width to get LAI for the rice plants can be used indirect or direct. We used that method in context with the first and second destructive harvest, so the plants were cut already. Because of the problem of leaf-rolling which occurred with the first harvest just after cutting we were looking for another method, instead of scanning, to compare the results with the LAI values measured with LAI2000. Hereby the length and width were measured with a tab meter. To calculate LAI, the data about length (L) and width (W) need to be inserted in the following formula suiting to the leaf shape of rice leaves (Sestak et al., 1971):

$$A = 0.857\ LW \tag{7}$$

2.8 Measurements after harvest

2.8.1 Time of harvesting

At several meetings at the field with the field assistants who are mostly farmers with practical knowledge in manual threshing, storing and milling rice we decided at which date the different treatments were harvested.

We began harvesting the full irrigated plots on the 06/5/2015. Continued with the LSI plots on the 13/5/2015 and finished the harvest with the rainfed plots on the 24/5/2015. Because of the late rain in April the plants at the rainfed plot started growing and flowering again. For the comparison of all treatments one would expect, that a simultaneous harvest of all plots would have been reasonable. But the heterogeneity between the treatments led to another decision. The last additional water availability was a chance for the rainfed plants to gain yield. When the plants at the FI treatment were harvested, the rice plants at the rainfed plots were still in the milking stage. On the other hand side: By waiting to harvest the already harvestable plots we would have risked yield loss by bird destruction, other pests and fungi.

2.8.2 Method of harvesting

Three sub-samples per plot were harvested to separate stem, leaves and head, and stored them in three different bags. The three plants for the full irrigated and LSI plots were selected in the middle of the plot. The rainfed plots were very heterogeneous. Often only some plants were located in a single corner, so we changed to a random choice of the three plants for the sub-samples.

15 plants per plot (Q1) were harvested for total plant biomass determination and to calculate the harvest index. The overground biomass and the heads as yield component were stored separately. Because of the heterogeneity of some plots - on one side the plants looked very poor and the other side of the plots the plants were quite strong - plants from the diagonal were chosen (see Figure 20: Plot layout). Therefore the first and the last two rows were excluded, starting from the second row, one plant per row and dripper was included in Q1.

For total yield per plot the heads of all remaining plants were harvested (Q2). Therefore the stems were cut and the heads were collected.

2.8.3 Postharvest processes

To increase storability of the grain yields the heads dried outside of the bags, in the sun for 2 days. Further on the workers separated the seeds from the heads.

To get reliable seed weight values, in terms of yield analysis, the seed moisture content is a main factor. To determine the moisture content of the seeds we used the direct method of seed drying implementing the total removal of the water out of the spikelets. Three subsamples of 5 g per treatment were dried in the drying oven for 72 h at 105 °C to achieve the smallest standard deviation of grain moisture of rice (Chen, 2003). There are two possibilities to define grain moisture content: wet basis and dry basis. In this study only wet basis moisture content is used and calculated as the ratio of the water weight to the dry weight of the spikelets.

$$(MC) = (WR) \times 100 \times (GWD)^{-1} \quad (8)$$

For example a sample has a grain weight of 100 kg before drying *(GWD)* and 80 kg after drying the amount of water removed *(WR)* is 20 kg. Our calculations ends up by a moisture content *(MC)* of 20 % by x = 80 x 100 x 100^{-1}.

Rice seeds as any other hygroscopic material have a specific moisture equilibrium, depending on the seeds moisture content and the water vapour in the air. All parameters concerning yield data were calculated with a moisture content of 14 % (International Rice Research Institute) corresponding to a moisture equilibrium at 3200 Pa and 29 °C (San Martin et al., 2001).

Spikelets per head were counted differing between filled and unfilled spikelets. Thousand grain weight (TGW) was determined by counting three times 100 seeds out of the total amount of seeds harvested for Q1 for one plot (15 plants); weighed the subsamples, dried them in the oven as explained above and weighed them again. By knowing the moisture content at the time of counting is was possible to determine the TGW by upscaling the three times 100 to 1000 seeds.

2.9 Water use efficiency

To evaluate the efficiency of cropping systems, different definitions of water use efficiency were developed. The economic water use efficiency was used to determine the efficiency of the rice cropping treatments at our field trial and was calculated by dividing the yield (g/m^2) by the amount of water applied by irrigation and rainfall (mm).

The water supply of the treatments did vary according to the irrigated amount of water and the water gained through rainfall. Flat treatments lost water by run-off, treatments with tied ridges avoided run-off. The amount of water loss by run-off was calculated according to Wiyo et al. (2000) with the following formula:

$$\text{If } Ri > Rw;\ ROi = COEF/100 \times (Ri - Rw) \text{ and if } Ri < Rw;\ ROi = 0 \qquad (9)$$

Referring to the soil moisture data in chapter 2.5 the rainfall coefficient (COEF) is 38 and the threshold amount (Rw) is 4.9. The surface run-off (ROi) was calculated on a daily base according to the daily inputs of rain (Ri). The amount of rainwater which was theoretically available for R, LSI and FI treatments was reduced by the amount of run-off. For detailed information about the water use and the irrigation schedule see Table 2 and Table 3.

2.10 Analysis

To download and process the data for the LAI2000 Plant Canopy Analyzer the program FV2200 2.0 (LI-COR Biosciences, Inc., Nebraska USA, 2000) was used. EXCEL was used to download the arranged data from different devices. The analyses were made with STATISTICA. By using single and multiple ANOVA it was possible to determine significant differences between the treatments with a LSD-test ($p \leq 0.05$). Linear regression analyses were also performed with STATISTCA and SigmaPlot 10.0. Furthermore SigmaPlot 10.0 was used to create the graphs.

3 Results

3.1 Effect of water management on soil moisture availability

An interesting parameter in terms of soil moisture availability is the rainfall distribution within single rain events especially concerning the comparison of TR and flat treatments. Figure 24 is showing the four biggest rain events within the growing season 2015. That figure should illustrate the rainfall distribution within 24 hours, showing the total amount as well as to highlight that most of the rain is falling within several minutes.

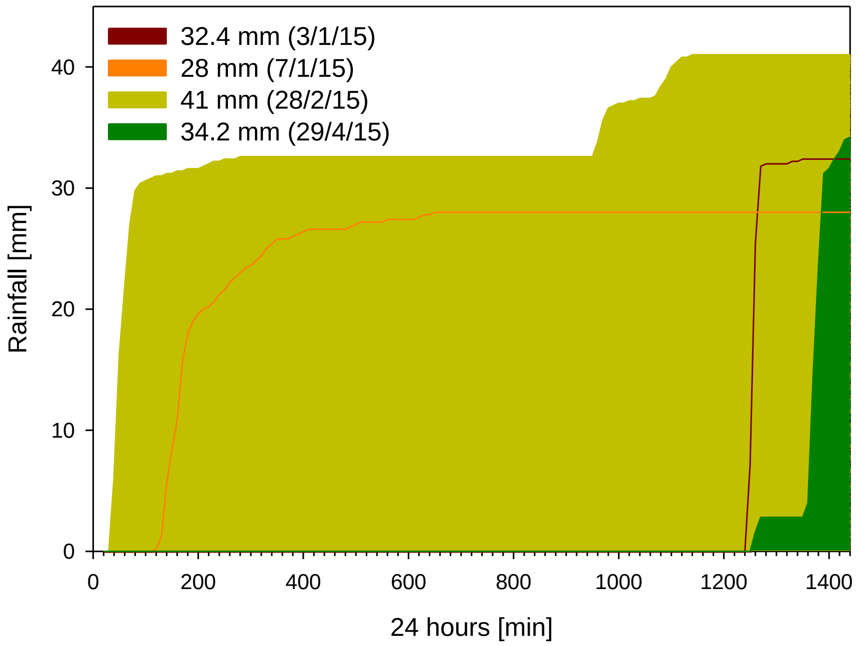


Figure 24: Rainfall distribution in mm of the four biggest rainfall events during the growing season 2015. 24 hours are distributed into 10 minutes intervals, according to the data delivered by the weather station nearby the field trial. Cumulative design represents the total amount of rainfall within one day as shown in the legend.

If the tied ridges had an influence on the soil moisture it should be visible in Figure 25 and Figure 26 whereby the average soil moisture of CW (left) and FW (right) treatments is shown as the variation of LSI + CW or LSI + FW (reference line) respectively (see absolute moisture contents in Figure 44 appendix). Thereby it seems that the soil surface moisture of the FI treatment was always higher than at the other treatments no matter if weeded or not. Figure 25 is illustrating the soil moisture at the soil surface. Whereby the fully irrigated treatments with FW reached higher soil surface moisture values compared to the CW treatment in relationship to the LSI treatments. The rainfed plots, only influenced by rainfall show reasonably most of the time lower soil surface moisture values than the LSI treatments. At the FW treatments the tied ridges seemed to have a higher positive influence on the soil surface moisture content of the TR + LSI treatment with FW than at the TR + LSI treatment with CW.

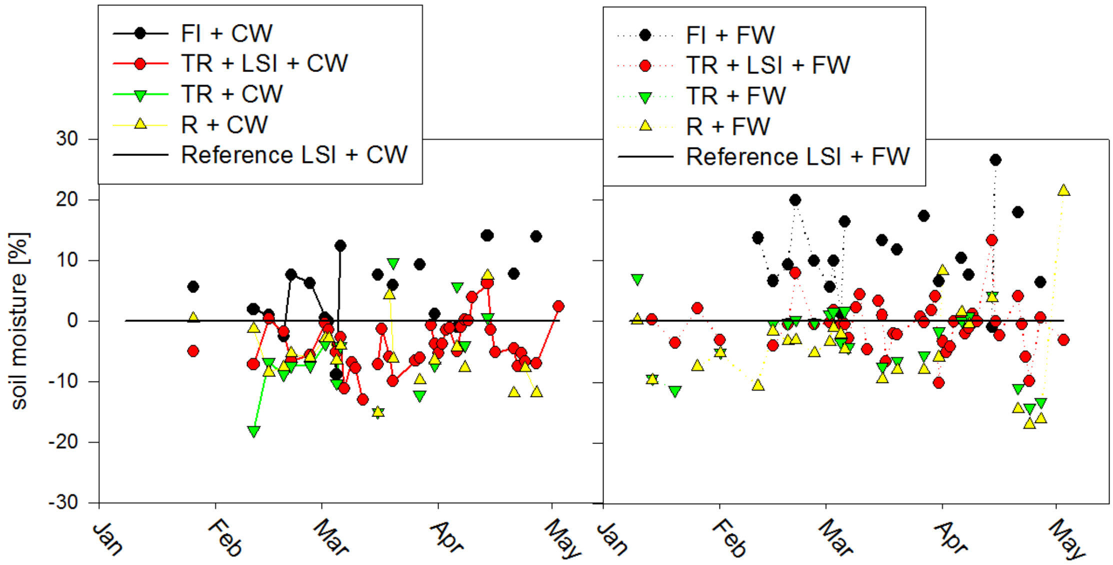


Figure 25: Soil surface moisture measured by SM300 of CW treatments (left side) and FW treatments (right side) in deviation to the LSI treatment (black line) as treatment with the highest soil moisture resolution.

Figure 26 is showing the soil moisture measured by PR2 in 10, 20, 30 and 40 cm depths in variation to the LSI treatment (see absolute moisture contents in Figure 45 appendix). The LSI treatment was chosen as reference treatment because of the highest soil moisture resolution. Thereby the highest soil moisture content variations were observed in 20 cm depth in comparison to that reference. The TR + LSI + FW treatment showed higher soil moisture contents in 10, 20 and 40 cm depths compared to the reference treatment. At the CW treatments the LSI treatment had higher soil moisture contents than the TR + LSI treatment (especially in 10 cm depth). At measurements after April all treatments showed more or less higher soil moisture contents in 20 cm depth than the reference. In 30 cm depth the soil moisture content of the R treatment without tied ridges and CW/FW often exceeded the soil moisture content of the reference. The soil moisture of TR + LSI treatments was most of the time less than at the reference. At the CW treatments the soil moisture is nearby the reference values in 40 cm depth. Interestingly the soil moisture in 40 cm depth at the FW treatments was almost always more compared to the reference.

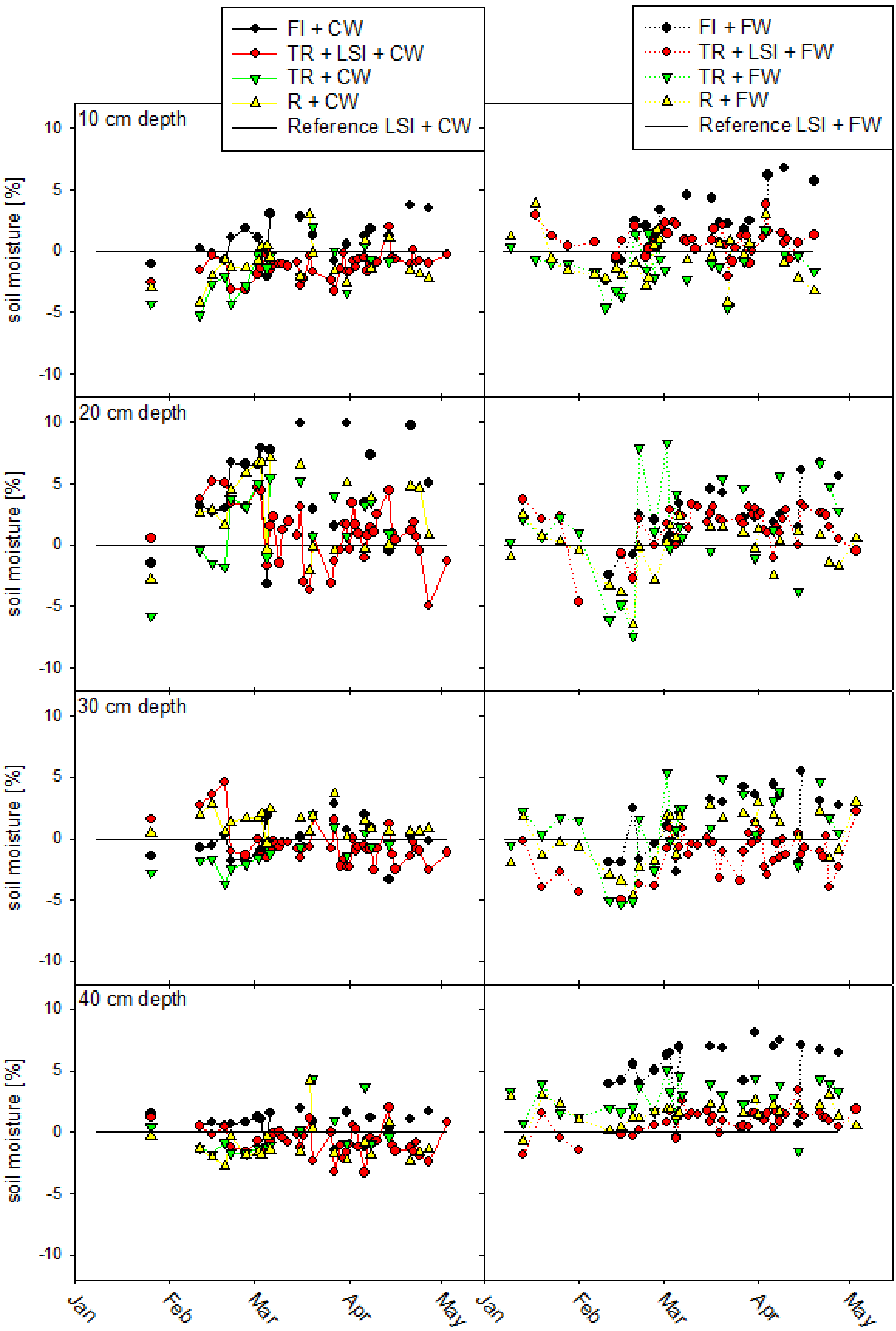


Figure 26: Soil moisture in four depths measured by PR2 of CW treatments (left) and FW treatments (right) in deviation to the LSI treatment (black line) as treatment with the highest soil moisture resolution.

To highlight the differences of soil moisture contents between weeded and less weeded treatments, treatments within one water management method were compared by linear regression according to the soil moisture content of CW and FW treatments (Figure 27). The linear regression delivered the following output:

5 cm depth: FI: $R^2 = 0.5912$, $y = 0.8886x + 4.6727$, LSI: $R^2 = 0.6552$, $y = 0.6618x + 2.1458$, TR + LSI: $R^2 = 0.4893$, $y = 0.5255x + 5.8557$, TR: $R^2 = 0.5031$, $y = 0.6803x + 4.6927$, R: $R^2 = 0.4778$, $y = 0.857x - 0.3967$;

10 cm depth: FI: $R^2 = 0.3591$, $y = 0.6723x + 6.7169$, LSI: $R^2 = 0.7648$, $y = 0.8434x + 1.7168$, TR + LSI: $R^2 = 0.3585$, $y = 0.5375x + 9.2837$, TR: $R^2 = 0.0294$, $y = 0.5562x + 7.8079$, R: $R^2 = 0.3669$, $y = 0.7978x + 3.1762$;

20 cm depth: FI: $R^2 = 0.8523$, $y = 0.7176x + 3.5687$, LSI: $R^2 = 0.3707$, $y = 0.5599x + 7.1237$, TR + LSI: $R^2 = 0.2649$, $y = 0.2949x + 12.15$, TR: $R^2 = 0.0891$, $y = 0.5265x + 9.0613$, R: $R^2= 0.012$, $y = -0.1405x + 18.465$;

30cm depth: FI: $R^2 = 0.1617$, $y = 0.658x + 5.7771$, LSI: $R^2 = 0.1916$, $y = 0.787x + 1.5358$, TR + LSI: $R^2 = 0.2483$, $y = 0.2976x + 7.9284$, TR: $R^2 = 0.1434$, $y = 1.1228x - 0.1434$, R: $R^2 = 0.122$, $y = 0.2356x + 11.011$;

40cm depth: FI: $R^2 = 0.8086$, $y = 1.2339x - 2.8631$, LSI: $R^2 = 0.0723$, $y = -0.3235x + 18.855$, TR + LSI: $R^2 = 0.2619$, $y = 0.4275x + 7.5326$, TR: $R^2 = 0.0031$, $y = -0.0318x + 17.145$, R: $R^2 = 0.0486$, $y = 0.2497x + 11.728$;

All depths (10 - 40 cm): FI: $R^2 = 0.7581$, $y = 1.0102x - 0.3142$, LSI: $R^2 = 0.6633$, $y = 1.2278x + 51996$, TR + LSI: $R^2 = 0.4698$, $y = 0.4204x + 8.8794$, TR: $R^2 = 0.12$, $y = 0.5844x + 7.3865$, R: $R^2 = 0.0958$, $y = 0.4451x + 8.5764$;

Linear regression: $P \leq 0.05$ *, $P \leq 0.01$ **, $P \leq 0.001$ ***, n.s. = not significant

Treatment CW*Day:	Treatment***, day***
Treatment FW*Day:	Treatment***, day***
Treatment*Day*Weeding:	Treatment***, day***, weeding **;
	FI: day n.s., weeding n.s.;
	LSI: day ***, weeding ***;
	TR + LSI: day ***, weeding n.s.;
	TR: day n.s., weeding n.s.;
	R: day **, weeding n.s.

The soil moisture contents between LSI + FW and TR + LSI + FW were significant. The average moisture content at the plot with tied ridges was higher than without TR. The plots with LSI and farmer`s weeding also reached significantly higher soil moisture contents with TR than without. The day of measurement was significantly important for the soil moisture contents of weeded and less weeded plots.

The soil moisture contents of rainfed plots with clean weeding were not significantly different from plots with TR or without. The rainfed plots with FW also showed no significantly different variation of soil moisture contents concerning plots with or without TR.

To check if the weeding component influenced the soil drying up I compared the daily soil moisture change of LSI + CW with LSI + FW and TR + LSI + CW with TR + LSI + FW. Additionally by comparing LSI + CW with TR + LSI + CW and LSI + FW with TR + LSI + FW I also tried to identify the effect of tied ridges on soil drying up. Hereby I chose five days in a row where the treatments were not irrigated because the water requirements were satisfied by rain. Reasonably the day of measurement had a significant effect on soil moisture change. The weeding component and the TR did not result in a significant change of soil moisture change.

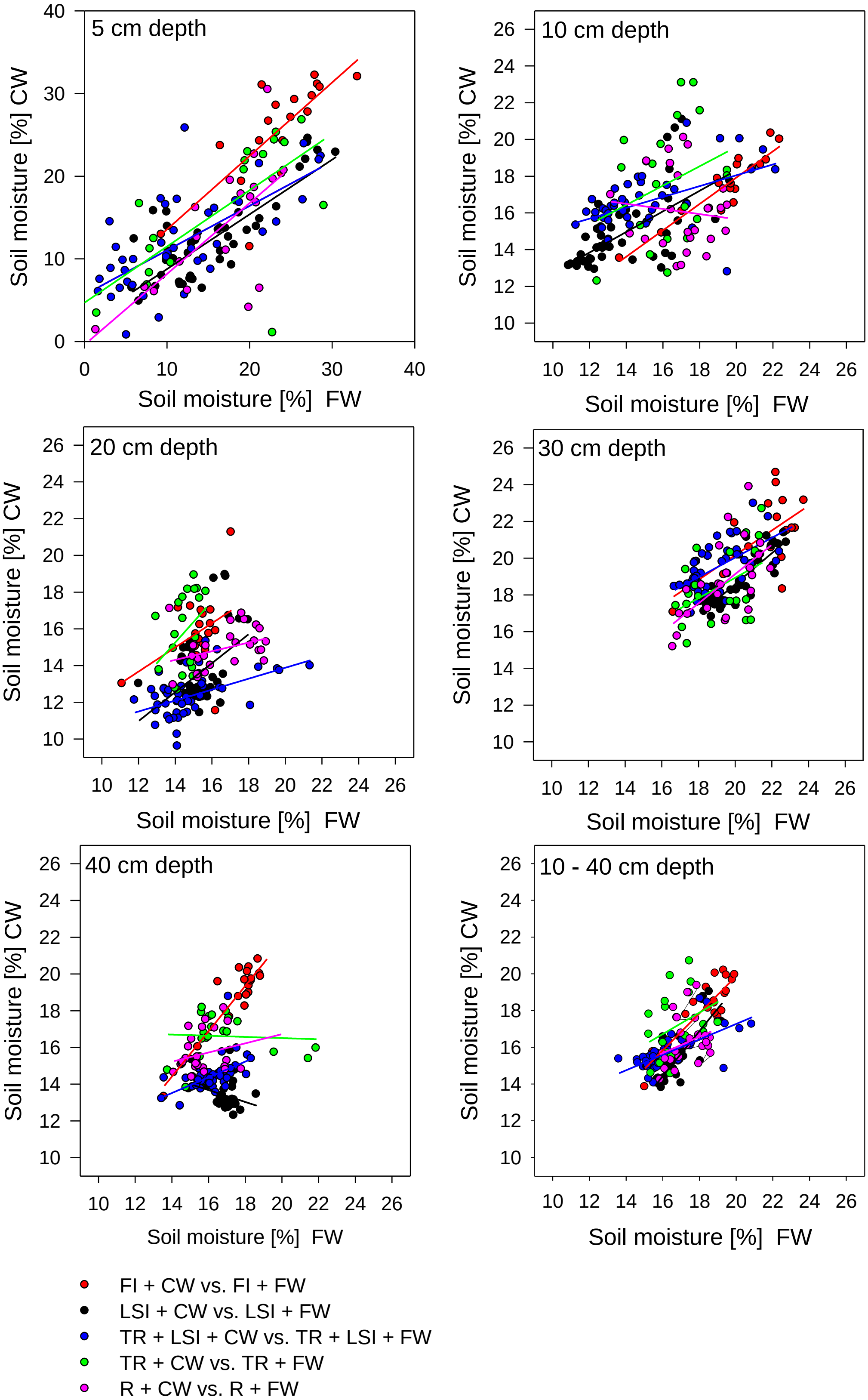


Figure 27: Soil surface moisture and soil moisture in 10 - 40 cm depths and the average of 10 - 40 cm depths and their regression curves. Y-axes: Clean weed treatments (CW), x-axis: Treatments with farmer`s weeding (FW).

3.2 Effect of weeding on microclimate

To identify if weeds at the less weeded treatments competed for water with the rice plants or promoted the togetherness, microclimate data was analyzed in addition to the soil moisture contents shown in the previous chapter. Figure 27 is illustrating the variation of humidity and temperature from March until the middle of May for a plot with total crop water supply with CW and with FW. The temperature was measured on the soil surface and in 10 cm height from the soil within the canopy. The humidity was also measured 10 cm above the soil. The humidity within the canopy was mostly higher at the CW treatment, especially in March with poor rainfall. In April the humidity at the FW plot exceeded the humidity measured at the CW plot. At the big rain event at the beginning of May the humidity of the CW treatment strongly decreased, whereas the humidity at the FW increased. By using multiple regression to compare the measured humidity of the CW treatment with the FW treatment, the day of measurement as well as the weeding component had a significant effect on the humidity within the canopy (R^2 = 0.3620). By comparing the temperature 10 cm above the soil for the two different treatments, the day of measurement influenced the temperature significantly. The weeding component had no significant effect on the temperature within the canopy (R^2 = 0.1826). Thereby the temperature within the canopy at the FW treatment exceeded mostly the temperature measured at the CW treatment. The same trend occurred by comparing the surface temperature. The surface temperature was significantly influenced by the day of measurement as well as the weeding component (R^2 = 0.6796).

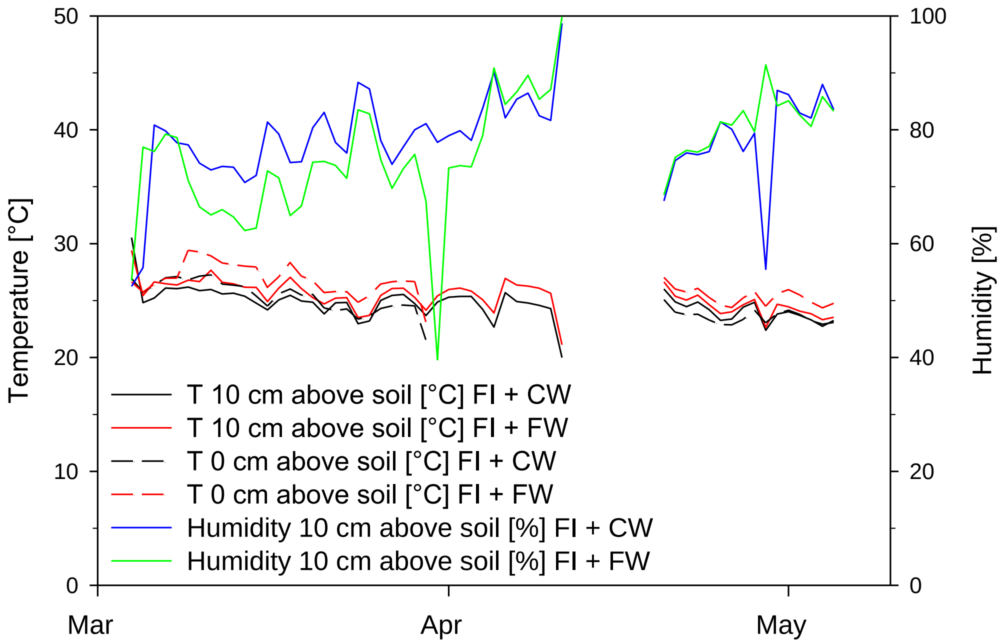


Figure 27: Temperature and humidity for a treatment with full water supply (FI) with CW or FW from March until the middle of May. Humidity and temperature 10 cm above the soil and additionally temperature at the soil surface.

3.3 Effect of soil moisture availability on phenological development

The phenological development was observed according to the different treatments with different amounts of water supply. A specific BBCH state according to Lancashire et al. (1991) was reached if more than 50 % of the plants showed that specific development. Figure 28 is only showing the phenological development of the rice plants within the CW treatments. The plants at the FW treatments didn't show a visual different development to those. The rainfed treatment without TR reached the BBCH of stem elongation latest of all treatments (58 DAS). The two rainfed treatments started booting more or less 70 DAS. Whereby the plants at the irrigated treatments developed similar until heading (70 DAS), the rainfed treatments never reached the BBCH of heading. The irrigated plants with full water supply reached and left the BBCH of flowering earliest and developed fruits within two weeks followed by ripening 88 DAS. There were no differences in phenological development between the plants at TR + LSI and LSI treatments. Those treatments reached maturity 127 DAS; one week later than the plants at the FI treatment.

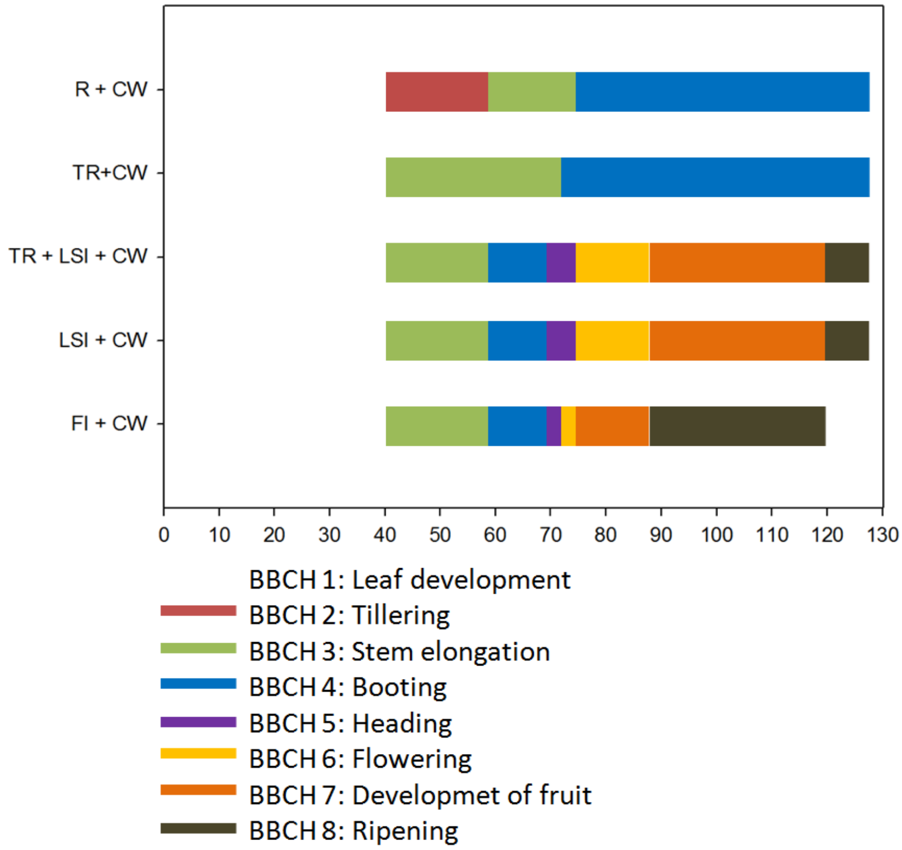


Figure 28: Phenological development of the rice plants within in the different CW treatments according to the days after sowing (Lancashire et al., 1991).

3.4 Effect of soil moisture availability on plant total biomass

According to Fofana and Rauber (2000) is the amount of weed biomass strongly related to grain yield. This chapter is showing how much biomass was produced per hectare. Thereby the biomass production was split into biomass of weeds and rice plants; thereby again separated into grain yield and straw yield (Figure 29). 64 DAS after sowing the FI treatments had the significantly highest amount of weeds with 3.6 t/ha. That amount of weeds which grew within 64 DAS and the final harvest (120 - 128 DAS) was 1.5 ^{A}, 1.8 ^{AB}, 1.1 ^{BC}, 0.7 ^{C} and 0.92 ^{C} t/ha for the FW treatments FI, LSI, TR + LSI, TR and R respectively.

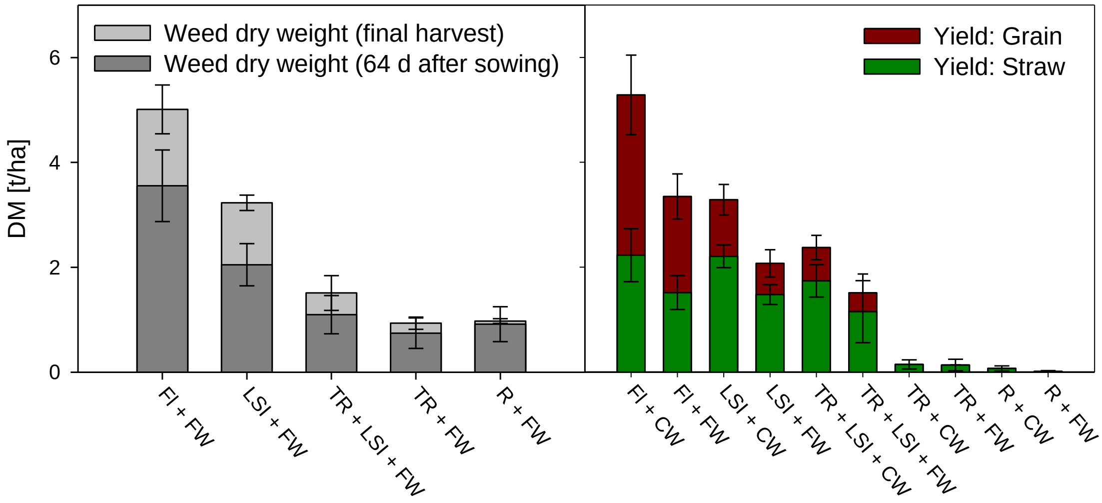


Figure 29: Dry mass production according to the different treatments separated into weed biomass (left) harvest two times and the grain and straw yield (right) of rice determined at the final harvest (yield/ha calculated with the plot specific plant density); Weed dry weight: FI + FW: n = 4, LSI + FW: n = 3, TR + LSI + FW: n = 2, TR + FW: n = 4, R + FW: n = 4; Yield: FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 2, TR + CW: n = 4, TR + FW: n = 4, R + CW: n = 4, R + FW: n = 4.

The rice plants at the FI + **CW** treatment produced the most biomass: straw and grain. The grain yield with 3.1 t/ha was significantly higher at the FI + CW treatment as at any other treatment. The amount of straw yield produced at the rainfed treatments was significantly less than at the irrigated treatments. By comparing the total biomass (straw and grain) of the rice plants, the plants at the FI + CW treatment had a total biomass of 5.3 t/ha which was significantly higher than at the CW treatments TR + LSI, TR and R which achieved a rice biomass production of 2.4, 0.1 and 0.1 t/ha respectively. The treatments with life saving irrigation also reached significantly higher biomass yields than the rainfed treatments. The LSI treatment with a biomass amount of 3.3 t/ha was not different compared to the yield produced under FI and TR + LSI conditions.

The rainfed treatments with **FW** achieved a significantly lower straw biomass than the irrigated treatments with more than 1 t/ha. The grain yield of the FI + FW treatment with 1.8 t/ha was significantly higher in comparison with the LSI and rainfed plots. By focusing on the total produced biomass, including straw and grain, the FW + FI, LSI, TR + LSI, TR + R reached 3.3 ^{A}, 2.1 ^{AB}, 1.5 ^{BC}, 0.1 ^{C} and 0.0 ^{C} t/ha respectively.

The linear relationship (R^2 = 0.69032590) between dry weed weight and rice yield was highly significant.

3.5 Effect of soil moisture availability on dry mass partitioning

Figure 30 a), b), and c) illustrate the absolute amount of biomass in gram invested into leaves, stem, head and seeds. Those parameters were collected three times: 49 DAS, 82 DAS and at the final harvest 120 DAS.

A) is showing the dry mass partitioning 49 DAS. Thereby plants at the FI + FW treatment reached the highest total dry mass, as well as the highest values for leaves and stem. The leaf weight of plants grown under FI + **CW** conditions was with 1.6 g significantly higher than of the plants grown under rainfed conditions.

Also at the **FW** treatments the rice plants grown under FI conditions reached the highest leaf and stem dry weight. The stem dry weight was significantly higher compared to any other FW treatment and the leaf and stem weight was significantly higher than at plants grown at TR + LSI, TR and R treatments.

The relationship according to stem and leaf dry weight between FW and CW treatments was not significant 46 DAS within a specific water management treatment.

The dry weight of leaves and stems was significantly different 82 DAS between plants grown under TR + LSI + **CW** or R + CW conditions, whereby the TR + LSI treatment reached the highest leaves and stem dry weight of all treatments (**b**).

Within the **FW** treatments the plants grown at the FI treatment reached the highest leaf dry weight with 3.1 g, which was significantly higher than plants at the LSI, TR and R treatment produced. The difference of leaf dry weight between LSI with and without TR as well as between rainfed treatments with and without TR was not significant. The stem dry weight produced by plants at the FI treatment was significantly higher than at the other treatments (except the TR + LSI treatment). The stem dry weight of plants at the LSI and the rainfed treatments did not vary significantly.

There were no significant differences 82 DAS according to leaf or stem dry weight by comparing plants grown under CW and FW treatments within a specific water management treatment.

At the final harvest (**c**) the stem dry mass of the plants at the **CW** treatments at FI and TR + LSI was significantly higher than at the plants which grown under rainfed conditions. Plants grown under LSI and CW conditions showed no significantly different stem dry weight to plants either at TR + LSI or at rainfed treatments. The produced leaf biomass was not different between all treatments. The seed weight of plants at the FI + CW treatment was significantly higher than at plants grown under rainfed conditions.

The leaf, stem and head (without seeds) weight, at the different **FW** treatments, did not show any significant differences. The weight of produced seeds at the FI + FW treatment was significantly higher than at the TR + FW treatment.

The relationship according to leaf, stem, head (without seeds) and seed weight at the final harvest, between FW and CW treatments, was not significant within a specific water management treatment.

Figure 30 **d**) and **e**) show the dry matter partitioning in % which was calculated on the basis of relative changes in dry weight. Thereby, as already shown in Figure 28, did plants with higher water availability invested earlier into reproductive organs. Within the change from the 49th DAS until the 82th DAS (**d**) only the irrigated plants showed biomass partitioning into the heads. Furthermore, from the 82th DAS (**c**) until harvest, the irrigated plants (except of the plants at the LSI + FW and TR + LSI + FW) invested next to 100 % of the biomass gain into the heads proportionally.

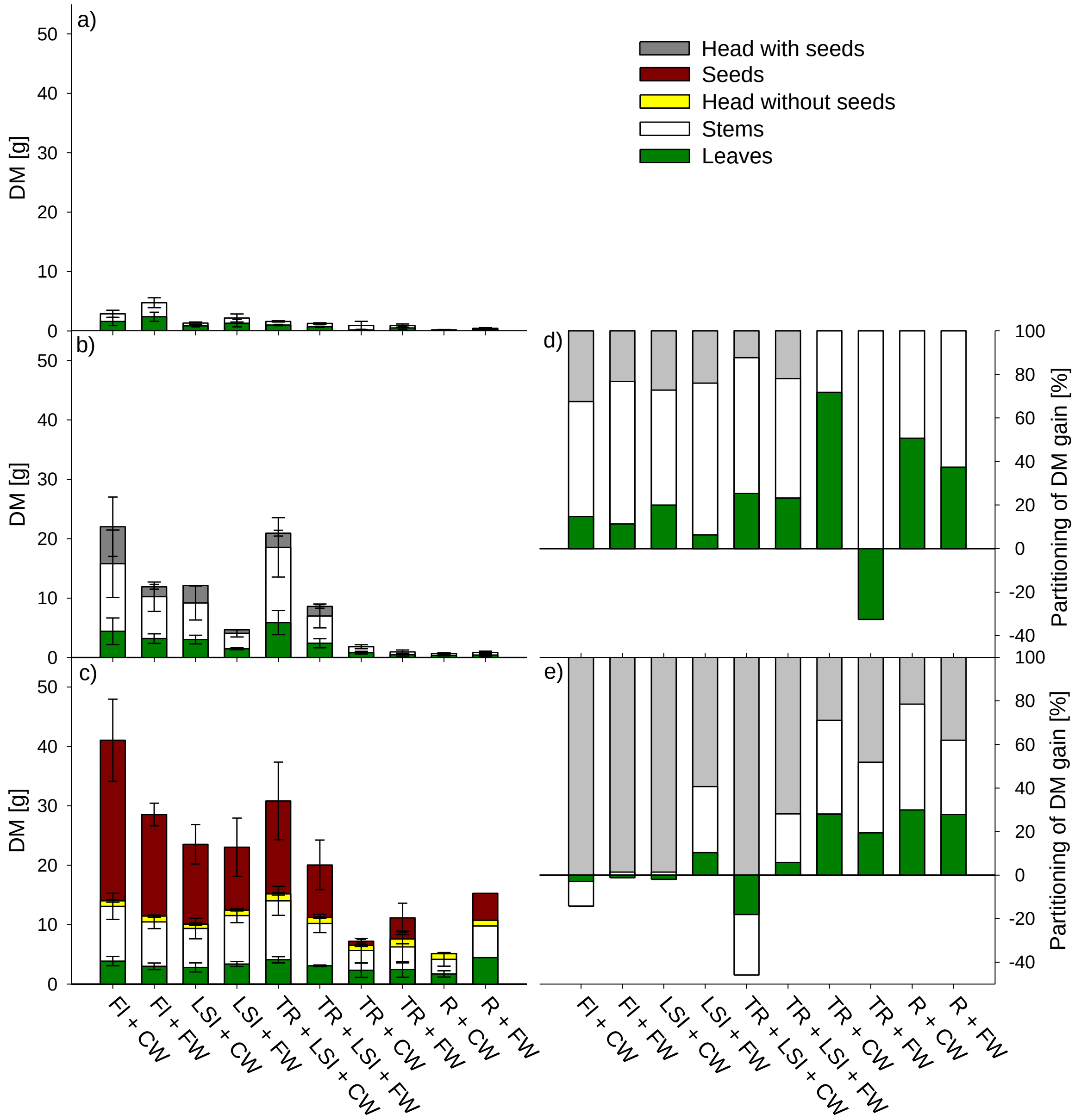


Figure 30: Biomass partitioning for 3 elected plants per plot; a) 49 DAS, b) 82 DAS, c) Final harvest, d) Dry matter (DM) partitioning on the basis of relative changes in dry weight from 49 DAS until 82 DAS, e) Dry matter partitioning on the basis of relative changes in dry weight from 82 DAS until final harvest; 49 DAS: FI + CW: n = 3, FI + FW: n = 3, LSI + CW: n = 2, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 2, TR + FW: n = 4, R + CW: n = 2, R + FW: n = 4; 82 DAS: FI + CW: n = 3, FI + FW: n = 3, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 3, TR + FW: n = 3, R + CW: n = 3, R + FW: n = 3; 121 DAS: FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 4, TR + FW: n = 4, R + CW: n = 3, R + FW: n = 1.

3.6 Effect of soil moisture availability on yield components

3.6.1 Leaf area index, specific leaf area

LAI was measured six times during the growing period 2015; 46, 63, 66, 79, 86, 101 DAS. The short interval between 63 and 66 DAS corresponds to the weeding in between those two days to determine the amount of LAI which is related to weeds.

Differences within CW treatments:
Comparing the LAI values of the plants grown under different CW conditions the values were not significantly different at 46, 66, 86 ad 101 DAS. At the 86th and 101th DAS the rainfed plots were excluded from the analysis because of the repetition which was too low. At the 63th and 79th DAS the LAI values from irrigated plants were significantly different from non-irrigated plants (R treatment excluded). Within the whole growing period the LAI of the rainfed plants (CW) was less than 0.3 and did not change significantly (Figure 31, top).

The plants which were irrigated with the full amount of required water within the CW treatments had the highest LAI throughout the whole season; plants under LSI conditions less than under FI conditions, and TR + LSI less than under LSI conditions. Plants at the FI, LSI and the TR + LSI treatments increased their LAI significantly from 46 DAS to 63 DAS. Additionally the LAI at the TR + LSI treatment did increase significantly from day 66 after sowing to the 79th DAS.

Differences within FW treatments:
The LAI for the irrigated treatments increased a lot from day 46 to the 63th DAS, compared to the clean weeded treatments, which is related to the weed biomass accumulation. Through the weeding within the 63th and 66th DAS the LAI decreased from around 4 (FI treatment) down to 0.4 by the removal of weeds. LAI at the LSI treatment was significantly different from the TR treatment at the 46th DAS. At day 63 after sowing the plants at the fully irrigated treatment reached the significantly highest LAI. The plants at the LSI treatment reached a LAI of 2.4 which was significantly different from the LAI reached at the FI, TR + LSI, TR and R treatments. At day 79 after sowing the plants at the FI treatment reached significantly higher LAI values, compared to the LAI values at rainfed plots. At the 86th and the 101th DAS the LAI values for all FW treatments were not significantly different (rainfed treatments excluded).

The LAI of the plants at the FI, LSI and TR treatment increased significantly from 46th to 63th after sowing and decreased significantly after weeding (from the 63th to the 66th DAS). Additionally the LAI for the plants grown under rainfed conditions decreased significantly from day 79 to day 101 after sowing for the TR treatments and from 63 DAS to 66 DAS for the R treatments.

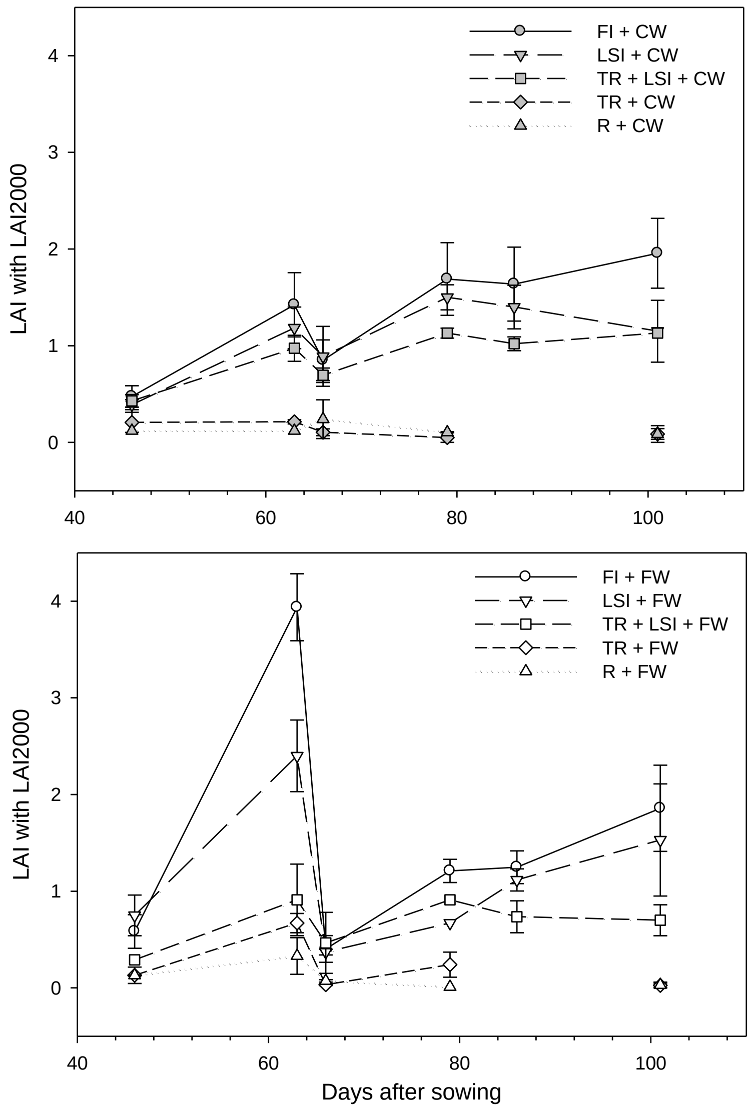


Figure 31: LAI measured with LAI2000 for CW treatments (top) and FW treatments (bottom) according to 6 different measuring days after sowing, for all treatments except of TR + LSI + FW (n = 2) is n = 3.

Figure 32 is showing the comparison of three different LAI measuring techniques at clean weeded treatments. The black dots are showing the LAI values measured with LAI2000. Those values are corresponding to the LAI values shown in Figure 31, 79 days after sowing. The LAI values calculated by scanning, shown with red dots, were measured during the 2nd destructive harvest 82 days after sowing. Hereby three plants per treatment were harvested and the leaves scanned. By using the average amount of plants per treatment the leaf area per plot was upscaled to leaf area per m^2. By using the formula in chapter 2.7.3.3 the information of leaf length and width was used to estimate leaf area per plant and finally, as explained at LAI by scanning, per m^2 (green dots).

By scanning the leaves and processing the scanned pictures the treatments FI, LSI, TR + LSI, TR and R reached a LAI of 1.3, 0.8, 0.9, 0.0, and 0.0 respectively. By calculating the LAI on the base of length and width of the leaves the treatments FI, LSI, TR + LSI, TR and R reached a LAI of 1.5, 1.0, 1.2, 0.0 and 0.0 respectively.

Significant differences of LAI between the different water management practices were already explained in the paragraph before. Interesting is the correlation between the different measuring techniques. By using linear regression to compare LAI by scanning and LAI measured with LAI2000 R^2 is 0.9181 (y = 1.2736x + 0.1236). A bigger correlation exists between LAI measuring by scanning and measuring length and width of the leaves; R^2 reached 0.9958 (y = 1.1678x + 0.0261).

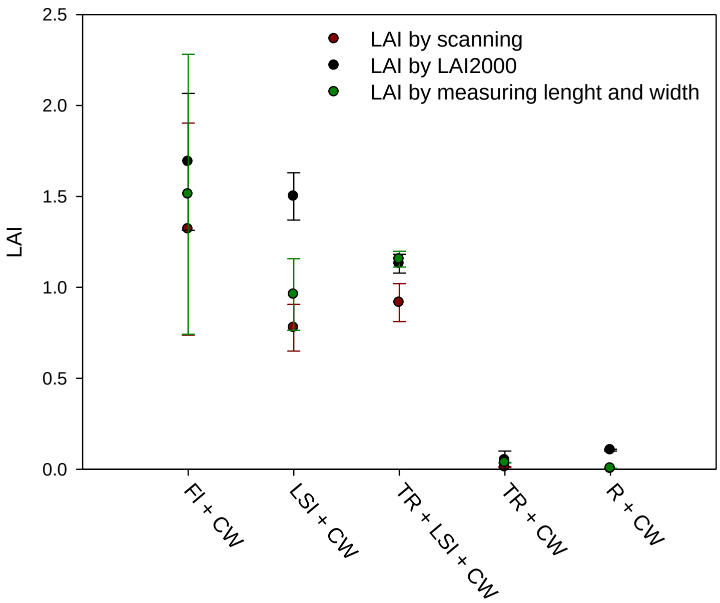


Figure 32: LAI results for clean weeded treatments with three different LAI measuring techniques: LAI measured by LAI2000, with leaf scanning, measuring length and width and calculating LAI with the formula shown in 2.7.3.3. LAI values above represent LAI measurements with LAI2000 79 days after sowing and LAI measurement by scanning and measuring length and width of leaves 82 DAS.

The specific leaf area (SLA) was calculated by dividing LAI by dry weight (DW) of the leaves. The following Figure 33 is showing the SLA for the treatments with CW (a) and for the treatments with FW (c). The LAI measured with LAI2000 was taken for a) and c). Because of the poor performance of the rainfed plots, the rainfed treatments were excluded in a) and c) because of the poor accuracy of LAI2000 with low LAI values. Graph b) was added to show that the SLA may vary according to which LAI measuring method was used.

SLA was thereby calculated by using the LAI determined by leaf scanning (79 DAS). But by using multiple regressions to compare SLA, which was calculated by using LAI from scanning or measured with LAI2000, the difference was not significant. The SLA values were not significantly different according to the different treatments or days after showing (46, 79, 121 DAS).

By measuring LAI with LAI2000 the rice plants at LSI + CW treatments showed higher SLA values than the rice plants at the FI + CW treatment, whereas the SLA value determined by scanning was lower. According to the Figure 32 which shows that the scanning and leaf measuring methods agree that the LAI was lower (< 0.5) than measured with LAI2000. Additionally the leaf weight used for SLA calculation came from the three plants which were used for scanning and leaf measuring. Hereby I would conclude that Figure 33 b) is more adequate than a) at 80 DAS.

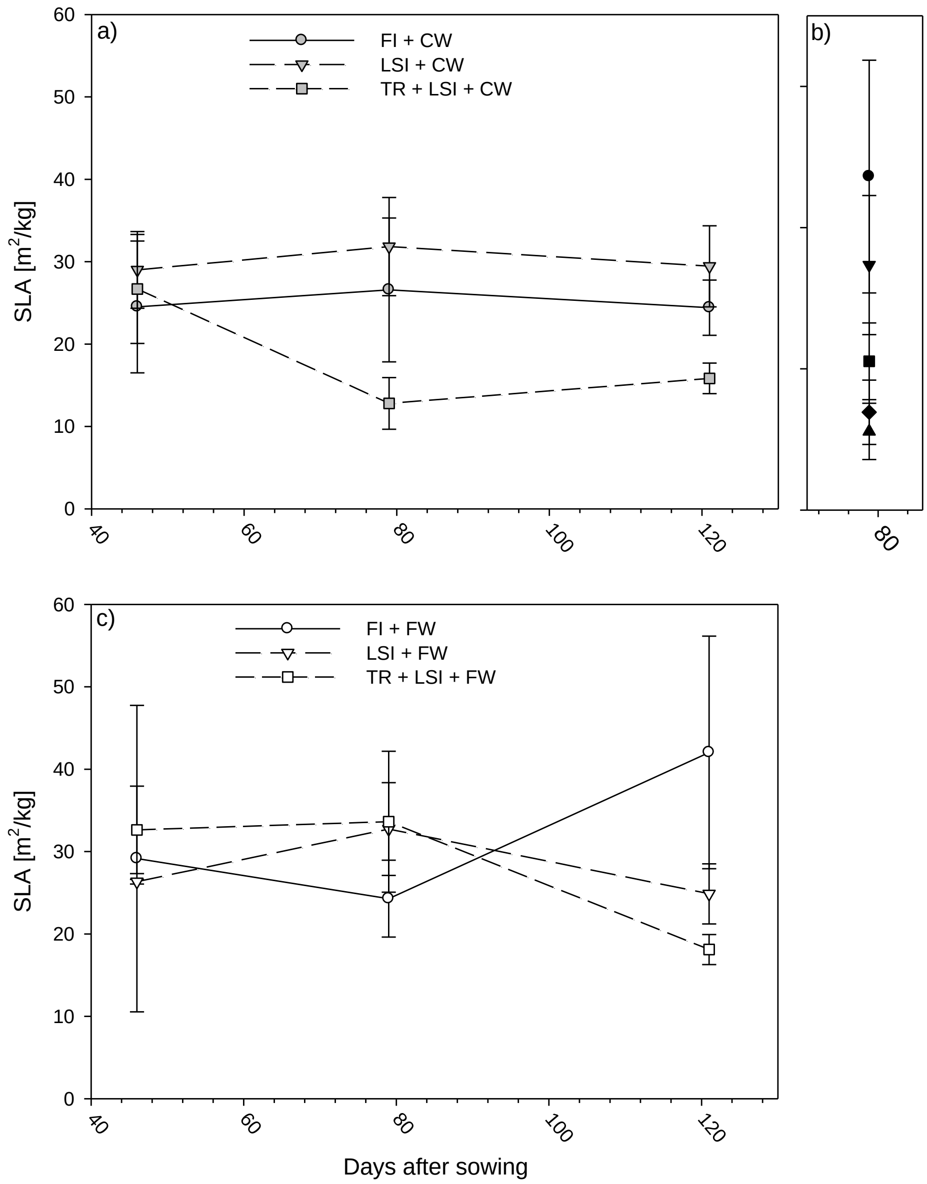


Figure 33: SLA in m²/kg for CW (a) and FW (b) treatments calculated by using LAI measured with LAI2000 (a, c) and by scanning of leaves (b). B) rotated quadrate: TR + CW, triangle: R + CW; 49 DAS: FI + CW: n = 3, FI + FW: n = 3, LSI + CW: n = 2, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 2, TR + FW: n = 4, R + CW: n = 3, R + FW: n = 4; 82 DAS: FI + CW: n = 3, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 3, TR + FW: n = 3, R + CW: n = 2, R + FW: n = 3; 121 DAS: FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 4, TR + FW: n = 4, R + CW: n = 3, R + FW: n = 1.

3.6.2 Yield determining components

This chapter includes the introduction of yield determining components which were measured for the ten different treatments. Table 7 is giving an overview about the average grain yield, the tillers per plant and the amount of productive tillers per plant. The amounts of filled and unfilled spikelets, together with the thousand grain weight (TGW) are additionally delivering information about the yield composition.

Table 7: Yield components for the ten different treatments according to the average amount of plants per m². Plant density per m² for the clean weeded treatments FI, LSI, TR + LSI, TR and R was 19.6 (± 0.4), 18.3 (± 0.69); 18.0 (± 0.4), 2.8 (± 0.8) and 2.0 (± 0.7) respectively. The treatments FI, LSI, TR + LSI, TR and R with farmer`s weeding reached 16.8 (± 1.6), 15.5 (± 0.7), 13.4 (± 1.7), 2.2 (± 0.7) and 0.8 (± 0.3) plants per m² respectively; Significant differences with LSD-test (p ≤ 0.05) = Small letters: comparison of CW treatments; capital letters: comparison of FW treatments; *: comparison of CW and FW within one water management treatment; Grain yield, Tillers per plant, productive tillers per plant: FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 4, TR + FW: n = 4, R + CW: n = 4, R + FW: n = 4; Filled spikelets per head: FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 4, TR + FW: n = 2, R + CW: n = 2, R + FW: n = 1; Tillers per plant: TGW: FI + CW: n = 4, FI + FW: n = 3, LSI + CW: n = 1, LSI + FW: n = 3, TR + LSI + CW: n = 2, TR + LSI + FW: n = 1, TR + FW: n = 1.

	Grain yield [g/m²]		Tillers per plant		Productive tillers per plant [%]		Filled spikelets per head		Unfilled spikelets per head		TGW [g]	
FI + CW	301.9 a	± 75.0	7.9 ab	± 0.7	86.7 a	± 8.0	100.1 a	± 8.5	7.2 b	± 1.2	27.7 a	± 0.6
FI + FW	181.0 A	± 42.6	6.8 A	± 0.9	82.3 A	± 8.7	80.2 A	± 8.1	9.2 B	± 0.7	27.2 A	± 0.7
LSI + CW	106.5 b	± 28.8	7.6 ab	± 1.9	84.2 a	± 9.4	74.8 ab	± 6.2	16.2 b	± 1.1	22.4 b	± 0.0
LSI + FW	58.7 B	± 25.8	8.2 A	± 1.6	70.0 A	± 9.6	61.4 AB	± 27.8	24.5 AB	± 0.4	21.4 A	± 2.2
TR + LSI + CW	62.6 b	± 23.1	10.4 a	± 1.0	70.7 a	± 10.4	63.3 abc	± 10.9	25.4 b	± 1.8	21.8 b	± 0.7
TR + LSI + FW	36.3 B	± 34.2	9.1 A	± 1.2	64.9 A	± 15.0	51.3 AB	± 21.5	33.3 AB	± 1.0	22.3 A	± 0.0
TR + CW	0.1 b	± 0.1	4.7 b	± 1.4	14.4 b	± 14.4	31.8 bc	± 25.0	60.0 a	± 0.7	--	--
TR + FW	0.1 B	± 0.1	6.4 A	± 2.4	27.9 B	± 9.9	15.7 AB	± 3.4	53.6 A	± 2.9	21.3	± 0.0
R + CW	0.1 b	± 0.1	4.2 b	± 1.6	23.6 b	± 16.3	5.2 c*	± 0.5	69.2 a	± 0.3	--	--
R + FW	0.0 B	± 0.0	1.6 B	± 1.6	18.4 B	± 18.4	22.7 B*	± 0.0	37.3 AB	± 0.0	--	--

Within one treatment with a specific water management method (for example within FI treatments) the **grain yield** was not significantly different between treatments with CW or FW. Although the average grain yield of the CW treatments for the treatments FI, LSI and TR + LSI reached circa double the amount as for the treatments with FW.
The fully irrigated treatment reached the highest average grain yield within the treatments with CW with 301.9 g/m^2, which was significantly different from all other CW treatments.
Also the FI treatment with FW reached the significantly highest grain yield of 181.0 g/m^2. The lowest grain yield of 0.1 g/m^2 was measured at the rainfed treatment without TR. The tied ridges did not improve the yield significantly for the rainfed and the treatments with LSI.

The treatment TR + LSI reached the highest number of **tillers per plant** within the CW treatments with 10.4, that number was significantly different from the number of tillers per plant for the rainfed treatments. The lowest average number of tillers per plant of 4.2 reached the rainfed treatment without TR. The highest numbers of tillers with 9.2 per plant at the FW treatments was also reached at the treatment with TR + LSI. The rainfed plants grown at the treatment without TR had the lowest number of tillers per plant with 1.6.
The rainfed treatment with TR (FW) reached a significantly higher number of tillers per plant in comparison with the rainfed treatment without TR (FW).

The percentage of **productive tillers per plant** did not vary significantly within one water management treatment (comparing CW and FW). The TR had no significant effect on the percentage of productive tillers per plant. The fully irrigated treatment with CW reached the highest number of 86 % productive tillers. The irrigated treatments showed significantly different numbers of productive tillers according to the rainfed treatments.

The amount of **filled spikelets** was different between the FW and the CW treatment at the rainfed treatments without TR. But that difference should be unattended because of the low number to repetitions. The highest number of filled spikelets was reached by the FI + CW treatments with 100. The treatments with LSI showed no significant differences to that number of filled spikelets. The trend within the CW treatments was similar to the FW treatments.

The LSI + CW treatment showed similar yield determining components in comparison with the FI + FW treatment but seemed to suffer from the stem borer attack resulting in a higher amount of **unfilled spikelets**. The irrigated CW treatments showed significantly less numbers of unfilled spikelets per plant (7.2) in contrast to the rainfed treatments where the number increased up to 69. At the FW treatments the fully irrigated treatments still reached the lowest number of unfilled spikelets. That number was significantly different from the number of unfilled spikelets for plants grown under rainfed conditions. The plants at the rainfed treatments without TR and treatments with LSI showed no significantly different number of unfilled spikelets in comparison with fully irrigated or rainfed plants with TR.

The **TGW** at the FI and clean weeded treatments reached 27.7 g and decreased down to 21.8 g for plants at the TR + LSI treatment. The difference of TGW between plants grown under FI and LSI conditions was significant. Within the treatments with FW the TGW did not vary significantly. The grain yield for the rainfed treatments was too low to determine TGW.

The average yield per treatment was additionally determined by the number of plants per treatment. The average plant density per m^2 for the clean weeded treatments FI, LSI, TR + LSI, TR and R was 19.6 (± 0.4), 18.3 (± 0.69); 18.0 (± 0.4), 2.8 (± 0.8) and 2.0 (± 0.7) respectively. The treatments FI, LSI, TR + LSI, TR and R with farmers weeding reached 16.8 (± 1.6), 15.5 (± 0.7), 13.4 (± 1.7), 2.2 (± 0.7) and 0.8 (± 0.3) plants per m^2 respectively. By calculating the possible yield on the base of 23.6 plants per m^2 the CW treatments FI, LSI, TR + LSI, TR and R would have reached an average yield (g/m^2) of 363.6, 137.3, 82.1, 0.8 and 0.9 respectively. Supposed that treatments with farmer`s weeding had 23.6 plants per m^2, the treatments FI, LSI, TR + LSI, TR and R would have reached an average yield (g/m^2) of 254.3, 89.3, 63.9, 0.8 and 0.0 respectively.

Figure 34 is illustrating the harvest index of all treatments which resulted by dividing:

$$\text{Grain harvest index} = (\text{Grain yield}) / (\text{Grain + straw yield}) \qquad (10)$$

The highest shoot dry weight of 450 g/m^2 was reached by the plants from the LSI + CW treatment, followed by the FI treatment and then the TR + LSI treatment. The shoot dry weight of the plants at the weeded and irrigated treatments was significantly different from the shoot dry weight from plants at rainfed plots.

The significantly lowest shoot dry weight with 34 g/m^2 at the FW treatments in comparison with the irrigated treatments was reached by rainfed plants without TR. The highest shoot dry weight for the FW treatments with 390 g/m^2 was reached at the LSI treatment.

By comparing plants grown under FI + CW and FI + FW conditions the shoot dry weight was significantly different. The weeds at the LSI treatments did also reduce shoot dry weight of the rice plants significantly.

There were no significant differences by comparing the grain yield of CW with their corresponding FW treatment within one treatment with different water supply. The highest grain yield was achieved by plants grown under water requirement fulfillment and clean weeded conditions with 650 g/m^2. That yield was significantly different within all treatments with CW.

The highest yield with 265 g/m^2 within the FW treatments was also reached by rice plants at the FI treatment. The rainfed plots reached reasonably the lowest grain yield. Significantly different yields within the FW treatments were reached by comparing the FI treatment with the TR + LSI and the rainfed treatments.

The similar observation could be determined for the Harvest Index (HI) results. The Harvest index reached no significantly different values between the CW and the FW treatments at treatments with specific water supply. The highest HI with 58 was reached by plants at the FI + CW treatment. That value reached at the fully irrigated treatment was significantly different in comparison with all other CW treatments. The HI for plants grown under rainfed conditions were additionally significantly different from treatments with LSI.

The highest HI for plants grown under FW conditions was reached by the FI treatment with 51, which was significantly different from the HI reached at other treatments. The lowest HI with two was reached by the rainfed plot without TR within the FW treatments, which was significantly different from LSI treatments. The LSI treatments reached different HI values in comparison with rainfed treatments but plants at the TR + LSI showed no significant difference in comparison with rice plants at the rainfed + TR treatment.

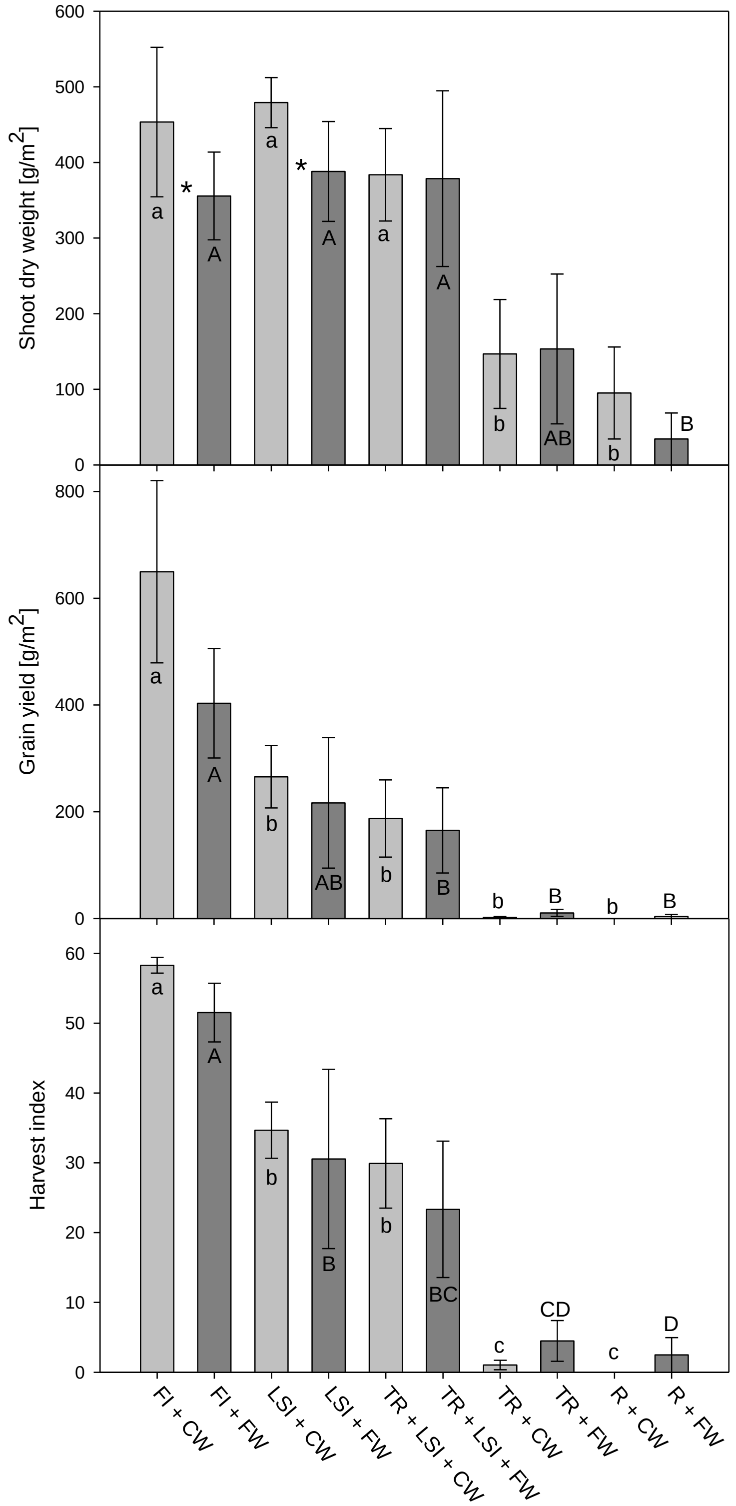


Figure 34: Harvest index for different treatments. Resulting in division of grain yield (middle) and shoot dry weight (top) for 40 plants per m^2 (calculated by harvesting 18 plants). Significant differences with LSD-test ($p \leq 0.05$) = Small letters: comparison of CW treatments; capital letters: comparison of FW treatments; *: comparison of CW and FW within one water management treatment. FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 4, TR + FW: n = 4, R + CW: n = 4, R + FW: n = 4.

3.6.3 Water use efficiency

The efficiency of water use for grain production is shown in Table 8. Hereby the rice plants at the FI treatments reached the highest water use efficiency (WUE) with 0.41 g m^{-2} mm^{-2} which is still less than at experiments of Borrell et al. (1997), whereby the rice cropping system reached a WUE of 0.66 g m^{-2} mm^{-2} with a similar water use of 762 mm. The weeds reduced the WUE of the treatment with full irrigation and farmer`s weeding by 40 %. Interestingly the rice plants grown under the life saving irrigation with clean weeding reached an even higher WUE with 0.26 g m^{-2} mm^{-2} than the plants grown under FI + FW conditions. The very low grain yield of the rice plants at the rainfed treatments lead to a WUE of 0 g m^{-2} mm^{-2}. Caused by White heads the grain yield was, in context to the used water management, partly tremendously reduced. To consider that the White heads could have been avoided the table does also include the potential WUE which results out of the potentially possible grain yield which could have been harvested without yield loss caused by White heads (Table 9).

Table 8: Water use efficiency with archived yield and with potential yield without the yield losses caused by White heads.

Treatment	Yield [g m^{-2}]	Potential yield [g m^{-2}]	Water use [mm]	WUE [g m^{-2} mm^{-2}]	Potential WUE [g m^{-2} mm^{-2}]
FI+CW	301.94	319.06	730.91	0.41	0.44
FI+FW	181.02	194.71	730.91	0.25	0.27
LSI+CW	106.50	124.27	412.16	0.26	0.30
LSI+FW	58.66	78.69	412.16	0.14	0.19
TR+LSI+CW	62.64	78.72	483.87	0.13	0.16
TR+LSI+FW	36.29	49.53	483.87	0.08	0.10
TR+CW	0.09	0.17	294.20	0.00	0.00
TR+FW	0.07	0.13	294.20	0.00	0.00
R+FW	0.07	0.14	222.50	0.00	0.00
R+CW	0.00	0.00	222.50	0.00	0.00

3.7 Yield loss

Yield loss may occur at any growth stages by pest, diseases or abiotic stress factors. In addition to the induced water shortage without or reduced water supply, stemborers and weeds reduced grain yield and the effects will we discussed in this chapter.

3.7.1 White heads

Due to a pest with stemborers some treatments suffered and lost yield; close to a total yield failure. The White heads were probably the result of a stem borer attack, against whom we sprayed just after occurrence. Whereas the heads at the fully irrigated plots starting flowering (Figure 35), more and more White heads occurred at the plots with water shortage and defined yield loss already 73 DAS.

Figure 35: Comparison of a healthy head and a head with symptoms of White heading (right). Whereas heads at full irrigated plants (left) flowered, plants under water shortage (middle) showed increased symptoms of White heading.

Table 9 is showing the yield loss due to the occurrence of White heads. The amount of White heads was once estimated at the field for each plot and the amount of unfilled spikelets was counted after harvesting according to three harvested plants per plot. The amount of White heads for fully irrigated treatment was less than 5 %, whereas the treatments with LSI lost 15 to 30 % of fertile heads by stem borers. The treatments without additionally water supply had an amount of White heads between 65 and 97 %.

Table 9: Percentage of yield loss by stemborer resulting in White heads and percentage of unfilled spikelets. Potential yield results in a correction of the real grain yield plus the average of yield loss shown by White heads and unfilled spikelets. Significant differences with LSD-test ($p \leq 0.05$) = Small letters: comparison of CW treatments; capital letters: comparison of FW treatments; *: comparison of CW and FW within one water management treatment. FI + CW: n = 4, FI + FW: n = 4, LSI + CW: n = 3, LSI + FW: n = 3, TR + LSI + CW: n = 3, TR + LSI + FW: n = 3, TR + CW: n = 3, TR + FW: n = 2, R + CW: n = 2, R + FW: n = 1.

	White heads [%]		Unfilled spikelets [%]		Potential yield (g/m^2)
FI + CW	4.7 ^{b}	± 0.9	6.6 ^{b}	± 0.5	319.06
FI + FW	4.5 ^{B}	± 0.9	10.6 ^{B}	± 2.4	194.71
LSI + CW	15.8 ^{b}	± 6.0	17.6 ^{b}	± 3.1	124.27
LSI + FW	31.5 ^{AB}	± 24.9	36.8 ^{AB}	± 24.7	78.69
TR + LSI + CW	22.3 ^{a}	± 17.1	29.1 ^{b}	± 10.8	78.72
TR + LSI + FW	28.8 ^{AB}	± 11.0	44.8 ^{AB}	± 21.2	49.53
TR + CW	90.9 ^{a}	± 5.9	70.8 ^{a}	± 21.5	0.17
TR + FW	65.3 ^{A}	± 22.0	77.5 ^{A}	± 4.3	0.13
R + CW	96.9 ^{a}	± 3.1	93.0 ^{a*}	± 1.3	0.14
R + FW	70.6 ^{A}	± 0.0	62.2 ^{AB*}	± 0.0	0.00

3.7.2 Weed flora

To conclude about the effects of weeds within the rice cropping system at this specific area, it was interesting to identify the most common weed species and their distribution. Table 10 is showing the weed and crop density in percentage per m^2. 56 days after sowing the full irrigated plots showed the highest weed and crop density. Compared to the treatment with TR and LSI the difference in weed and crop density was significant. The TR + LSI treatment was the only one in comparison where the crop density exceeded the weed density. That proportion changed to the end of the growing season where the crop density increased and exceeded the weed density considerably. The weed density at the full irrigated plots was significantly higher in comparison with all treatments with FW. Whereby the weed density of the LSI, TR + LSI, TR and R treatments was not significantly different 56 and 140 days after sowing, the crop density for the rainfed plots was significantly lower.

Table 10: Weed and crops density 56 and 140 days after sowing according to treatments with FW. Capital letters: significant differences p ≤ 0.05 (LSD). FI + FW: n = 4, LSI + FW: n = 3, TR + LSI + FW: n = 2, TR + FW: n = 4, R + FW: n = 4.

	56 DAS		**140 DAS**	
	Weed [%/m^2]	Crop [%/m^2]	Weed [%/m^2]	Crop [%/m^2]
FI + FW	41.3 ± 3.1 ^{A}	32.5 ± 2.5 ^{A}	16.3 ± 5.5 ^{A}	37.5 ± 3.2 ^{A}
LSI + FW	31.7 ± 4.4 ^{AB}	30.0 ± 0.0 ^{A}	5.0 ± 0.0 ^{B}	33.3 ± 6.0 ^{AB}
TR + LSI + FW	12.5 ± 7.5 ^{B}	22.5 ± 2.5 ^{B}	3.0 ± 1.6 ^{B}	22.5 ± 7.5 ^{B}
TR + FW	23.8 ± 9.5 ^{AB}	3.8 ± 1.1 ^{C}	0.5 ± 0.3 ^{B}	1.5 ± 1.2 ^{C}
R + FW	32.5 ± 7.8 ^{AB}	5.0 ± 2.0 ^{C}	0.5 ± 0.5 ^{B}	0.3 ± 0.3 ^{C}

Some frequently observed weeds species at our field trail are shown in Figure 36 to Figure 41. *Acanthospermum hispidum* DC., *Ceratotheca sesamoide, Corchorus olitorius, Tribulus terrestris* and *Dactyloctenium giganteum B.S.Fisher & Schweick* were identified species (Germer, 2015). They are all herbs occurring in subtropical and tropical areas.

Figure 36: ***Acanthospermum hispidum*** **DC. Inflorescence and branch; Makutupora. Dodoma Region. Tanzania; 3/2015 © Alexandra Schappert (Germer, 2015).**

Figure 37: ***Ceratotheca sesamoides*** **Endl. Flowers; Makutupora. Dodoma Region. Tanzania; 3/2015 © Alexandra Schappert (Germer, 2015).**

Figure 38: ***Ceratotheca sesamoides*** **Endl. Branch; Makutupora. Dodoma Region. Tanzania; 3/2015 © Alexandra Schappert (Germer, 2015).**

Figure 39: ***Corchorus olitorius*** **L. Foliage and flowers; Makutupora. Dodoma Region. Tanzania; 3/2015 © Alexandra Schappert (Germer, 2015).**

Figure 40: ***Tribulus terrestris*** **L. Foliage; Makutupora. Dodoma Region. Tanzania; 3/2015 © Alexandra Schappert (Germer, 2015).**

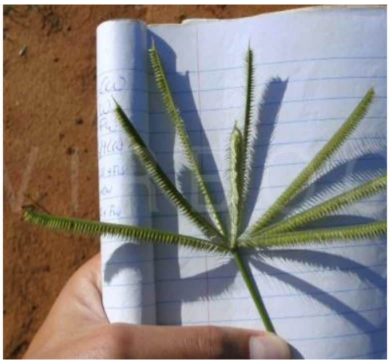


Figure 41: ***Dactyloctenium giganteum*** **B.S.Fisher & Schweick. Inflorescence; Makutupora, Dodoma Region, Tanzania; 3/2015 © Alexandra Schappert (Germer, 2015).**

4 Discussion

Rainfed systems in Dodoma are prone to drought because rain is only falling from October until May. Farmers practice implements to grow crops from January until May where the mean rainfall amounts to 429.4 mm (Table 5). During that growing season the rain is mainly falling from January until March and may provide enough rain to grow crops within a vegetation period of 150 days.

Cultivating upland rice in that region is no common practice although rice is a main component of the daily nutrition. As shown in Table 5 the mean amount of rain is less than the recommended amount of 450mm per season (Hijmans and Serraj. 2009). Matsumoto et al. (2014) described that NERICA with a yield of 3 t/ha needs 500 mm which exceeds the mean rainfall for Dodoma region. In addition to the total amount and need of rain, the rainfall distribution is causing bigger problems. De Datta, Surajit K. (1981) named the monthly recommend amount of rainfall of 200 mm. Dodoma region only reached a mean precipitation for the wettest months from January until March of 116 - 136 mm per month. Consequently Dodoma region is probably not well suited to grow upland rice just according to the yield determing parameter: water. This study aims to access if minimal water management may increase productivity of upland rice cropping systems in the semi-arid Dodoma region.

4.1 Effect of water management on soil moisture availability

According to Nyamangara and Nyagumbo (2010) the most important factor limiting crop productivity in SSA is soil fertility caused by inadequate soil moisture content. The soil moisture balance is depended on evaporation, transpiration, infiltration and internal drainage. The weeding component had significant influence on the soil moisture content in terms of changed water use and evaporation within the system. The evaporation seems to be reduced by weeds according to Okafor and Datta (1976). The Tiny tags which were installed in a plot with full water supply detected significant differences of humidity and soil surface temperature between CW and FW treatments. According to the collected data it was not possible to determine if evaporation of the soil increased, or increased transpiration of rice and weeds led to increased humidity. Interestingly the humidity of the FW treatment did exceed the humidity measured at a CW treatment in a moist month (April) and vice versa in a drier month (March). In conclusion, if the humidity changed in terms of changed

evaporation or transpiration can`t be drawn, because no measurements determining those parameters were conducted.
Weeds may have additionally caused gas exchange characteristics within the canopy and the environment.

Understandably treatments with more water input should show higher soil moisture contents. The amount of water use corresponding to the soil moisture content behavior is explained in this paragraph. The treatments with full water supply got 731 mm, including rain and irrigation water. Plants grown under life saving conditions had 44 % less available water than under FI conditions that corresponds to a difference of 318.7 mm water. Ali et al. (2015) explain that supplementary irrigation in combination with tied-ridging is causing higher soil moisture contents in comparison to cropping systems without water harvesting methods. This could also be observed at my field trial at different soil depths. Treatments with tied-ridging gained 71.7 mm more rainwater within their system, in contrast to flat treatments, where the same amount of rainwater was lost by surface run-off. Especially heavy short-term rainfalls as shown in Figure 24 are causing run-off because the infiltration capacity of the soil is exceeded. Figure 42 is showing how the water harvesting tied ridges collected water after a rainfall.

Figure 42: LSI treatment with rainwater filled tied ridges

According to the soil moisture contents measured frequently during the growing season the LSI treatment with tied-ridging (FW) showed significantly higher soil moisture contents especially in 10, 20 and 40 cm depths in comparison to the LSI treatment without tied ridges. The rainfed treatment with tied ridges had higher soil moisture contents than the flat treatment within the FW treatments. But the differences of soil moisture contents between rainfed plots with or without TR were not significant. The weeding component as well as the soil surface modification did not significantly influence soil drying after rain events.

4.2 Effect of water management on yield components

Leaf area index and specific leaf area

Drought stress decreases the leaf area (Anyia and Herzog, 2004) and the specific leaf area (SLA) (Liu and Stützel, 2004). According to the water use at

the different treatments (see Table 8) rice plants with the highest amount of available water had the highest LAI. Akinbile (2010) says that NERICA 4 may reach a LAI of 2.5 already 80 DAS (five times irrigation: 50 % ET covering). Whereby at this study the LAI never exceeded 2 with full water supply and agrees with results presented by Dingkuhn et al. (1998) for other upland rice varieties (WAB56-104). The LAI value decreased at the other treatments according to their water availability. The only exception was made by rice plants at the TR + LSI treatments which had a higher water availability than the rice plants at the LSI treatment without TR but showed a lower LAI.
Indirect LAI measurements include the comparison with a direct measured LAI to ensure reliability. Within this study we used scanning in combination with picture processing and leaf measuring in combination with leaf area calculation with a specific formula. Both directly LAI measuring methods only showed a small deviation which could be adapted with a better suiting formula for this specific leaf shape in an additional study. Measuring length and width seemed to be the best suiting low budget method for direct measured LAI for rice plants.

It has been observed that a reduction of the SLA is a way to improve water use efficiency (Wright et al., 1994). The presence of weeds seemed to influence this behavior especially in the early growth stages. The SLA, which is correlated to the LAI (Dingkuhn et al., 1998), was highest at rice plants with the highest water use - a high SLA corresponds to a low dry matter content of the leaves - and decreased by the amount of available water (CW treatments). The TR + LSI treatment is again not suiting to that relationship.
Decreasing SLA can be furthermore seen as a function of development stages (Dingkuhn et al., 1998). Anyia and Herzog (2004) assume furthermore from different studies, which are not directly related to upland rice, that there is a relationship between SLA with WUE and/or yield. This behavior seems to be similar at our study in that context, that rice plants grown at treatments with high SLA reached higher yields and WUEs as explained in the following chapters.

<u>Phenological development and biomasspartitioning</u>
Grain yield depends on the environment at all growing stages. Between germination an flowering droughts are causing development delay (Dingkuhn and Asch, 1999). In high, mid and low altitude the expected maturity of NERICA 4 rice is 160, 120 and 105 days respectively (Shrestha et al., 2009). The rice plants with the highest cumulative water use reached maturity earliest; the rainfed treatment with 222 - 294 mm water use did not reach maturity within the duration of our experiment (130 DAS) and invested, different to the other treatments, more than 15 % into leaf and more than 30 % into stem development whereas rice plants at other treatments already reached ripening. Within the 49th and the 82th DAS irrigated rice plants invested, in terms of

percentage of biomass gain, already into reproductive organs. Hereby the rice plants grown under life saving irrigation and clean weeded conditions invested more into productive tillers, than rice plants at the FI + FW treatments. The tied ridges at the LSI treatments induced that the rice plants invested less into reproductive organs than at the flat alternative with LSI. In between the 82th DAS and the harvest the rice plants under full water supply and the rice plants with LSI with or without tied ridges and clean weeding invested 100 % of their biomass gain into reproduction, whereas the competiveness between weeds and rice seemed to delay maturity of the rice plants grown under LSI with/without TR and farmer`s weeding conditions. This observation is approved by Dingkuhn et al. (1999), who says that leaf partitioning is positively affected by weed competiveness. But in difference to his study LAI, SLA and number of tillers did decrease by the existence of weeds in this study, which led to the conclusion, that other yield determining components were also not positively affected.

<u>Yield determining components</u>

Dingkuhn et al. (1999) describes that weeds in rainfed upland rice cropping systems may reduce yield up to 50 % and maybe even enlarged by poor soil fertility, diseases and pests. A side effect of the well adapted water availability was that weeds did also grew well and produced next to 5 t/ha of weed biomass which nearly equals the amount of biomass, which was totally produced by rice plants. Consequently by weed`s competitiveness, yield was decreased by 41 % (FI treatment).

Aerobic rice yields decrease already by 22 - 30 % (by an average soil moisture of 2 - 5 kPa in the season in 10 - 15 cm depth) in comparison to the flooded alternative (Bouman et al., 2005). Upland rice varieties express themselves with high yields due to high spikelet fertility, which is mainly caused by environmental stresses (Singh et al., 1990), and high harvest index (Bouman et al., 2005). All plants at the different treatments within this study grew at the same environment, only the water availability was different. Rice plants which were always supplied according to the crop water requirements performed best, in terms of plant development (growth stages) and yield determining components including LAI, SLA, number of tillers, number of spikelets etc. which did finally defined grain yield.

Reduced yield, reduced biomass growth and reduced leaf development are a result of water-stress but even occur without water deficit (Stürz, 2014). According to Singh et al. (1990) thermal stress is responsible for the percentage of spikelet fertility. Differences in microclimate according to the amounts of water applied by irrigation results in changed soil temperature and temperature at meristem level which are influencing yield components (Stürz, 2014). Weed competiveness as well as higher temperatures at meristem level may have caused yield loss. Higher temperatures measured at soil surface and 10 cm above the soil at the full irrigated treatment with farmer`s weeding decreased yield but had no significant effect on yield determining components in comparison with the clean weeded alternative.

Unfortunately White heads which probably occurred to a stem borer pest which complicates to conclude about grain yield differences between the treatments and their water management. Additionally the heterogeneity within the treatments as well as the heterogeneity within a single plot implies that some outcomes are a bit vague to assume the potential of the different water management practices finally.

Why did the yield (grain yield and biomass) decrease, but not significantly, at the life saving treatment with tied-ridging in comparison with life saving treatment without tied-ridging (for pictures see appendix 7.5)?

By having a look at the soil moisture deviation by comparing LSI and TR + LSI treatments the average soil moisture content in the treatment with TR seems to be less at least at the clean weeded treatments (Figure 26). But the idea that tied-ridging led to increased evaporation due to increased soil surface cannot persist by statistical analysis.

According to Ali et al. (2015) tied-ridging plus supplementary irrigating increased sorghum yield significantly compared to the control with supplementary irrigation without TR. The increase in crop yield can be defined as the run-off conservation efficiency (Krishna, 1989). According to Wiyo et al. (2000) tied-ridging may also cause yield loss in wet years, because rainwater is retained by tied ridges that would have been surface run-off. Nyamangara and Nyagumbo (2010) are naming the high rainfall which increased leaching in semi-arid areas due to increased drainage by tied-ridging. They additionally report that especially nitrates washed out of the root zone.
During the growing season in 2015 it rained 382.6 mm which is a dry year in comparison with the long term rainfall characteristics. Also the rainfall distribution was different. Especially in the comparable dry March with 27 mm instead of 117 mm, which is the long term average, the rice plants suffered. Nevertheless nutrient loss may be a reason why the life saving treatments with tied-ridging achieved lower yields and weed biomass compared to the LSI flat treatments. Whereby the water gain through water catching tied-ridging caused higher yields and biomass production at the non irrigated rainfed treatments, the tied ridges at the LSI treatment may have caused nutrient leaching out of the root zone and hence reduced yield. The water harvesting effect of tied-ridging is causing higher water infiltration by increased run-off, but may provoke an adaption of the fertilizer input.

<u>WUE</u>

Yang and Zhang (2010) named post-anthesis controlled soil drying as a method to enhance WUE. An enhancement of HI also improves WUE. Interestingly, the LSI + CW treatment produced the same amount of biomass as the FI + FW treatment, but the HI was worse for the plants at the life saving treatment. If the byproduct rice straw may be used reasonably the life saving management may be an option to produce satisfying grain yields in combination with rice straw usage.

If one or another water management was used, the FW treatments showed higher biomass productivity. The treatments with FW produced more biomass than the CW treatments of the same water management strategy, if weed biomass and rice plant biomass (straw plus grain) were included. Instead of the useless weeds, intercropping systems may be an opportunity to increase cropping intensity for weed suppression and the financial return (Singh et al., 1990).

4.3 Possibility to grow upland rice in Dodoma region

4.3.1 Tied ridges

Growing NERICA rice in Dodoma region without supplementary irrigation may lead to total failure. Tied-ridging is an option to increase yield in comparison to the flat cropping alternative (for pictures see appendix 7.5). Even at the first months when the amount and the distribution of rainfall were not extraordinary low in the year 2015 the plants died early (Figure 43, left). Thus tied ridges did not increase the yield, but it was visible that the plants were stronger. Nevertheless growing upland rice with tied-riding under rainfed conditions is no opportunity under the circumstances.

The water sensitivity of rice seems to be higher than for drought resistant plants like millet or sorghum which were also grown at our field trial as part of the ongoing PhD study. Those crops benefit stronger from the water harvesting tied ridges. Actually NERICA varieties were developed as stress resistant to water deficit and pests but as shown in this study, NERICA 4 is not adapted enough to the rainfed conditions in the Dodoma region and will probably not be integrated into the farmer`s cropping calendar as well as contributing to their earning capacities and food security. However, to confirm this statement additionally rice cropping seasons and seeds which are higher germinable are needed.

Tied ridges, a water harvesting basins (Figure 42) may also function as litter fall collection basins (Figure 43). Due to the avoidance of run-off, organic matter is lead into the basins formed by tied and ridges and may increase soil organic matter and thus improve plant nutrition. Buying mineral fertilizer is mostly not affordable for small scale farmers in rural areas. The creation and the maintaining of tied ridges is labor intensive but may trigger to benefits for semi-arid areas on a long term base (Krishna, 1989).

Figure 43: Tied ridges as a litter fall collection basins (right) and poorly developed rice plants 74 DAS under rainfed conditions in Dodoma (left).

4.3.2 Life saving irrigation

Farmers at the semi-arid Dodoma region don`t have the opportunity to irrigate that much water, that the crop water requirements are fulfilled within every growth stage by the lack of water access and water availability. Surface water usage in Tanzania is already a common practice for irrigation purposes according to the FAO. There was the idea developed to collect water during rainfalls and add it in rainless periods to upland rice cropping systems. The amount of water which was added at life saving irrigation in our study was base of the calculation about the implementation options of this imaginary project. The dimensions of rainfall harvesting methods in form of reservoir size or collecting area are even for a field size of 1000 m^2 not affordable. The inter-seasonal drought spell in March lasts 30 days. At the end of February it rained around 31 l. That amount of water needed to feed the system would be 77 l water per m^2, within a duration of 30 days before it rained again, to start rain water collection again. Even with a 28 mm rainfall and a 10 days rainless period within the middle of the rice growing season the size of water collecting methods would be immense, if not unrealistic.

Nonetheless supplementary irrigation is an opportunity to increase yield. The idea of life saving irrigation is to add enough water that the plants are not stressed. The decreased yield may be acceptable if the amount of water could be reduced to an affordable amount. At our study life saving irrigation was applied whenever drought symptoms occurred, especially in the drought period in March which was severe than normal. The Harvest index of plants grown under LSI conditions (CW and FW) was 41 % less than at the treatments with fulfillment of crop water requirements. Unfortunately the deficit irrigation at the water sensitive transition phase between vegetative and reproductive phase caused White heads, whereby the grain yield of the LSI treatments were additionally reduced. However, the WUE of the treatments with life saving irrigation was higher than at the treatments with FI and farmer`s weeding practice. Life saving irrigation with tied-riding did surprisingly caused no increased yield in comparison with the flat growing alternative.

4.3.3 Yield loss

20 to 30 % of the Tanzanians live in semi-arid areas. The poor rainfall distribution leads to drought periods and particularly inter-seasonal dry spells (Mongi et al., 2010). This is causing moisture stress and provokes yield loss in rainfed systems. Climate change is one of the most discussed phenomenon. However extreme rain events, if it’s causing floods or droughts, appear more frequently. Growing rainfed NERICA 4 in Dodoma region is, according to the data collected within this study, no opportunity to stabilize ecosystems to resist water deficit especially.

4.3.3.1 Water deficit

The sensitivity to water deficit varies during the vegetative and reproductive phase. Ingram and Yambao (1988) determined that water deficit during the vegetative phase had no effect on grain yield. In contrast, water deficit during the reproductive phase may cause 25 to 45 % yield loss in case of a 5 to 10 days lasting water deficit and may decrease yields up to 88 % if the water deficit lasts up to 15 days. Flowering, booting, dough and milking are named as considered most critical stages (Raemaekers, 2001). In March it rained only 27 mm which was mainly caused by one rain event at the beginning and at the end of this month. Hence especially rainfed plants suffered and yield loss was predicted. It is not certain that all White heads occurred in context with stem borers. For further information about the yield loss caused by White heads also in context with water shortage see 4.3.3.3. Crop duration seems to be a key parameter determining yield potential in rice cropping systems to escape, among other things, droughts. Therefore any delay in maturity, affected by weeds competiveness or water availability needs to be reduced.

4.3.3.2 Weeding

Weeds in upland rice system contribute considerably to the rice system productivity (Asch and Brueck, 2010). If rainfed rice is not weeded at all, Singh et al. (1990) expected a yield loss of 81 - 87 % in contrast to rice crops weeded by the farmer`s method, when the crops are weeded twice by hand. The yield loss caused by weeds was 1.23, 0.49, 0.27, 0.00 and 0.00 t/ha for the FW treatments FI, LSI, TR + LSI, TR and R respectively. That corresponds to a weed caused yield loss of 40, 46 and 41 % for the FI, LSI and LSI + TR treatments respectively. The weeding component had only significant influence concerning the amount of unfilled spikelets at rainfed treatments without TR, but did cause yield loss in all treatments with FW in comparison with the clean weeded alternative.

The profit of the upland rice growing system in Dodoma region may reach 266 €/ha under good management, sufficient water, proper fertilization, timely weeding, bird scaring and proper crop husbandry (Njovu, 2015). Some costs are reduced because household labor is used, consequently profit may increase. According to (Njovu, 2015; FAO, 2015) weeding at upland rice in Tanzania costs 85 € per ha. The rice price in Tanzania according to data from 2009 in the high season (July until august) is 350 Tanzania shillings per kg (0.15 €) and in the low season from (September until May) 500 Tanzania shillings per kg (0.21 €) (FAO, 2015). In context to the grain yield harvested at our field trial the full irrigated and clean weeded treatments would result in a turnover of 450 €/ha in the high season and 642 €/ha in the low season. The treatments with farmer`s weeding reach a turnover of 270 and 385 €/ha in the high and the low season respectively. The turnover reduced by weeding costs of the treatments with life saving irrigation is 74 €/ha for clean weeded and 88 €/ha for non weeded treatments. Hereby weeding had a negative impact on the turnover. But still life saving irrigation did not reach an affordable turnover to cover the costs of 294 €/ha for growing rice on the farmers own field until harvest.

Weed-crop interactions are strongly linked to crop density and soil fertility (Liebman and Gallandt, 1997). Due to the labor-intensive weeding in rice cropping systems and the environmental concern of using herbicides implement the cultivation of weed-competitive rice varieties. Thereby SLA and tillering may contribute significantly to weed competitiveness (Asch et al., 1999). A contribution to rice competitiveness with weeds effecting yield potential in low-management conditions maybe to promote high SLA during the vegetative growth and low SLA during the reproductive phase (Dingkuhn et al., 1998) or to implement intercropping systems.

4.3.3.3 Diseases and pests

According to our results shown at 3.7.1 yield loss, shown as unfilled spikelets and White heads, was 65 up to 90 % concerning rainfed treatments, 15 to 30 % at treatments with LSI and less than 5 % at fully irrigated treatments. One should conclude that the probability of yield loss correlates with the amount of water applied at a specific growth period. Akinbile and Sangodoyin (2015) agree on that idea that water shortage leads to White heads. The amount of 3047 mm, 2656 mm and 1789 mm lead to 7.4, 15.7 and 16.1 % of White heads respectively. In their study they observed the occurrence of White heads 78 DAP. At our field trial White heads occurred obviously 73 DAS. If deficit irrigation would be an option to enable upland rice cropping systems in semi-arid areas, water shortage should not lead to yield loss due to pets. There might be the option to avoid yield loss induced by stem borers by disclaiming water stress in the sensitive period when the plants are prone for White heads, although the NERICA 4 variety showed higher tolerance against stem borers than other NERICA varieties (Rodenburg et al., 2006).

Interestingly the ripening rice plants did not attract birds in comparison to the other crops at our field trial like sunflower, sorghum and millet. Bird scaring after emergence maybe reduced and reduce rice growing costs with up to 85 €/ha (Njovu, 2015).

4.3.4 Outlook

NERICA varieties with high yield potential combined with stress tolerance seem to suit to semi-arid areas. But seed costs and availability are still limited in rural areas in contrast to the low rice prices (Rodenburg et al., 2006). To grow upland rice successfully, fertilizer, pesticides and finally water are necessary and limit the suitability to grow upland rice in Dodoma region. Tied Ridging is a possibility to promote soil moisture contents and may also increase soil fertility also on a long term base, but did not trigger satisfying yields in the growing season 2015. Deficit irrigation improves grain yield but the costs for the equipment and the knowledge to avoid yield loss by water shortage in sensitive growth stages are linked to well implementation. Weed removal is labor intensive, but weed competiveness caused unacceptable yield loss in already low-input and low-outcome cropping systems. Therefore good strategies need to be applied to decrease negative effects of weeds by intercropping systems, crop density or crop competiveness. Related to data collected by this study rainfed upland rice cropping systems will not contribute to improved earning capacities and food security in Dodoma region. But more research is needed to finally discard the idea of growing upland rice in this area, especially long term studies about the effects of tied ridges, about deficit irrigation and crop establishment in early growth stages, are required.

5 Conclusion

Rice cropping systems are often considered as water intensive and therefore not suited for seasonal drought prone areas. In rainfed systems precipitation often exceeds crop water requirements at a specific rain event. Additionally temporal distributions in terms of drought spells lead to suboptimal water supply. Managing water access may improve water productivity during intervals between rain events with insufficient water supply from precipitation.
The main ideas of this study may help to grow successful NERICA 4 upland rice under local conditions in semi-arid areas like in Dodoma region. Therefore several water management practices like an adapted weeding management were implemented. Furthermore by adding a minimum amount of water, the soil moisture was kept above the permanent wilting point (life saving irrigation). Additionally the effects of minimal water management in case of modifying the soil surface to collect and save water, like tied ridges, were studied.

Time based weeding (farmer`s weeding) influenced the microclimate within the canopy in the treatment with full water supply (FI) in comparison to the clean weeded alternative. Soil moisture contents are significantly influenced by the weeding strategy, but soil drying after rain events was not affected. At all water management treatments the less weeded treatments showed a lower harvest index` (HI) and yields. Hence one could conclude that the effects on the microclimate within the canopy led to decreased fertility and furthermore that water competitiveness by the water use of weeds influenced the water availability for the rice crop negatively. Although the negative impact of the weeds on yield determining components and finally on the grain yield was not significant.
Water availability influenced weed and crop density and their competitiveness for water and light. Rice cropping with the farmer`s weeding strategy reached leaf area index (LAI) values up to 4 for FI treatments (~2.5 LSI treatments). After removing the weeds, rice plants at irrigated treatment showed LAI values smaller than 0.5, which is still lower than LAI values for rice plants at their corresponding clean weeded treatments. The specific leaf area (SLA) was not affected by the weeding component.

Water-saving irrigation decreased yield as well as water productivity. In that context, it was not possible to produce more rice with less water. The rice cropping system with life saving irrigation showed a 40 % worse HI and a poor performance in terms of water use efficiencies (1 t/ha with 412 mm water use) in comparison with the rice plants grown under full water supply. Those plants reached a grain yield of 3 t/ha, which is acceptable for NERICA 4 varieties. Although life saving did not achieve the expected yields, repetitions with specific attendance at water sensitive stages to avoid especially White heads, maybe with better suiting upland varieties and/or higher germination rate in addition to a higher transplanting tolerance, could be an option to achieve better suitability for upland rice cropping systems in water limited areas in Dodoma region. Hereby the water competitiveness needs to be reduced by weed removal or weed suppression. Intercropping as well as total crop usage may also improve the productivity of the system.

Tied ridges as a rainwater conservation technique, is a combination of ridge furrows and earth ties forming micro-catchment basins in the field to decrease surface run-off and to improve grain yield. Thereby the precipitation distribution and the architecture of the tied ridges play a major role. In this study soil moisture contents were significantly influenced by tied-ridging but had no impact on soil drying after rainfalls. Although soil moisture contents at the LSI treatment with TR (FW) was improved, grain yield as well as weed biomass and density were lower than at treatments without tied-ridging.
The rainfed rice plants performed poorly (no grain yield recognizable). To conclude, that tied ridges improved water availability at the rainfed treatment could only be demonstrated in terms of the higher total biomass and the number of plants which survived. Although tied ridges may be an opportunity to decrease soil degradation in terms of reduced run-off and increasing organic matter content and may contribute to a sustainable rice cropping system.

In terms of changed climate conditions, the opportunity to mitigate extreme events such as droughts and floods needs to be provided through the choice of crops and the cropping calendar to ensure food and energy security (Asch and Huelsebusch, 2009). It is not reasonable to conclude out of this study, that upland rice cropping in Dodoma region is not advisable if water access and availability is limited. Nevertheless, the growing season 2015 is showing that the NERICA 4 variety does not ensure a secure and sustainable upland rice production for low-input systems in semi-arid areas in Tanzania.

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Declaration

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Hereby declare on my honor that the attached declaration has been independently prepared solely with the support of the listed literature references and that no information has been presented that has not been officially acknowledged.

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Co-Supervisor: Prof. Dr. Gerhards

Thesis topic: **Effects of water availability and water management on the performance of NERICA 4 under rainfed conditions in semi-arid areas. Tanzania**

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