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The Management Strategies of Pearl Millet Farmers to Cope with Seasonal Rainfall Variability in a Semi-Arid Agroclimate

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Abstract: Rainfed agriculture constitutes around 80% of the world's agricultural land, achieving the lowest on-farm crop yields and greatest on-farm water losses. Much of this land is in developing countries, including sub-Saharan Africa (SSA), where hunger is chronic. The primary constraint of rainfed agriculture—frequently experienced in SSA—is water scarcity, heightened by the unpredictability of season onset, erratic rainfall, as well as the inability of farmers to provide adequate soil and crop management. Farmers react differently to constraints, making a variety of choices—including the timing of planting, type of land cultivation, fertilization, and scattered fields, among many others. Limited information is available on the combined effects of these strategies for improving crop yield and water use efficiency (WUE). An experiment was co-conducted with farmers over four consecutive rainy seasons (2014–2018) in Tanzania, to evaluate these strategies for single and joint effects in improving yield and WUE on rainfed pearl millet (*Pennisetum glaucum* (L.) R.Br.). The treatments used were flat cultivation both without and with microdosing, as well as tied ridging without and with microdose interaction, with different planting dates depending on farmers' decisions. Results show that farmers react differently to the early, normal, or late onset of the rainy season, and cumulative rainfall during its onset, which affects their decisions regarding planting dates, yield, and WUE. Microdose fertilization increases both the yield and WUE of pearl millet significantly, with greater effects obtained using tied ridging compared to flat cultivation. For low-income smallholder farmers in a semi-arid agroclimate, using tied ridging with microdosing during early planting is an effective response to spatiotemporal rainfall variability and poor soils.

Keywords: planting dates; microdose fertilization; tied ridges; pearl millet yield; water use efficiency

1. Introduction

More than two-thirds of people suffering from severe food insecurity in the world are concentrated in Sub-Saharan Africa (SSA) and Southern Asia [1], where rainfed agriculture accounts for more than 80% of the agricultural land. In SSA, rainfed agriculture is a major activity for the economy and food security [2]. However, large yield gaps [3] and total harvest losses among farmers [4] are still prevalent. Rainfed agriculture is challenged by climate change, specifically low and erratic rainfall [5]. SSA is prone to water scarcity [6] annually it records the lowest average crop yields [7] and crop water use efficiency (WUE) values [6]. Molden [8] defines WUE as a physical mass of production or the economic value of produce per unit volume of water. In rainfed agriculture, the definition of WUE that relates biomass to grain yields per cumulative rainfall provides insights into how rainfall is efficiently used by crops. Lower values of WUE in rainfed agriculture highlight the potential for improvement [9]. The improvement of WUE reduces water loss through evaporation, promotes crop transpiration, and fosters increasing crop yields.

In SSA, the onset of the rainy season is not predictable, which leads to planning complications for planting operations [4,10]. In addition to the uncertainties regarding seasonal harvests and overall production [11,12] , SSA is well known for having highly degraded soils with low fertility levels [13,14]. Although the region records the lowest WUE values [6], farmers may be able to raise WUE by adopting proven agronomic and water management practices [9,15]. Ongoing efforts address crop management challenges at different scales and provide recommendations [16–20]. However, there are reasons why efforts are not widely undertaken by farmers [3]. Among them is the fact that smallholder farmers—who occupy a large percent of cultivated land are limited by their ability to purchase the required inputs and adopt improved management options [21,22].

In order to improve food availability and sustainability in SSA, tested and credible crop enhancement strategies should be prioritized for adoption [23]. The authors of [24] identify suitable crop management strategies among many options—prioritizing them as crop upgrading strategies (UPS) through a systemization method based on importance, affordability, possibility, and effectiveness at overcoming the production challenges of cereals for low-income farmers in semi-arid areas. The study recommends four UPSs: tied ridges (TR) ("Tied ridges are long, narrow, and elevated strips of land (a ridge) crossed by earthband within the furrow called ties" ([10], p. 4); microdose fertilization (MD) (the application of fertilizer in small quantities at the time of planting and/or during top dressing at a period between 21 and 28 days after emergence [24]); scattered fields; and varying planting dates [24]. Subsequently, the authors of [10] study the UPSs' performance for the "Okoa" variety of pearl millet *(Pennisetum glaucum (L.) R.Br.)*, finding that scattering fields reduces the risks of total harvest loss, while the use of tied ridges conserves soil moisture and improve yields more than flat cultivation. However, there is no on-farm exploration as to what extent these UPSs—individually or in combination—can increase the on-farm efficient use of seasonal rainfall, accounting for variations in the onset of the rainy season, changes to daily and seasonal rainfall, as well as farmers' decisions regarding planting dates. Therefore, the main objective of this study is to evaluate the management strategies used by pearl millet farmers in improving yield and water use efficiency in the midst of variable rainfall patterns in a semi-arid agroclimate. Our specific objectives are (i) to evaluate the effects of variable rainfall patterns on when-to-plant decisions (i.e., the choice of planting dates)—here, we tested the hypothesis that the choice of planting dates for any growing season is influenced by the onset of the rainy season and cumulative rainfall during its onset; (ii) to quantify the effects of planting dates on the yield and WUE of pearl millet—here, we test the hypothesis that variable planting dates for any growing season results in significant differences in the yield and WUE of pearl millet; and (iii) to evaluate the effects of practicing tied ridging and microdosing at variable planting dates on the yields and WUE of pearl millet—here, we test the hypothesis that when tied ridges and MD practices are applied at different planting dates, they significantly affect the yields and WUE of pearl millet.

2. Materials and Methods

2.1. Study Area Description

Experiments were conducted in Idifu village, Dodoma region, in central Tanzania (Figure 1) as a case study for SSA. Lying between latitudes 4°7″ and 7°21″ S and between longitudes 36°43″ and 35°5″ E, the region is a major producer of pearl millet. It has a semi-arid climate with a mean annual precipitation of 481 ± 183 mm (mean ± Standard Deviation (SD)), with an average temperature of 24 °C (data period 2010–2018). In the village, sandy soils dominate. They are found to contain a low total nitrogen (%) mean of 0.04 ± 0.02, mean pH (H_2O) of 6.7 ± 0.9, and a low mean soil organic matter (%) of 0.74 ± 0.35 (mean ± S.D). As shown in Figure 1, soil groups (according to different groups of the World Reference Base (WRB) Soil Groups [25]) varied across the village.

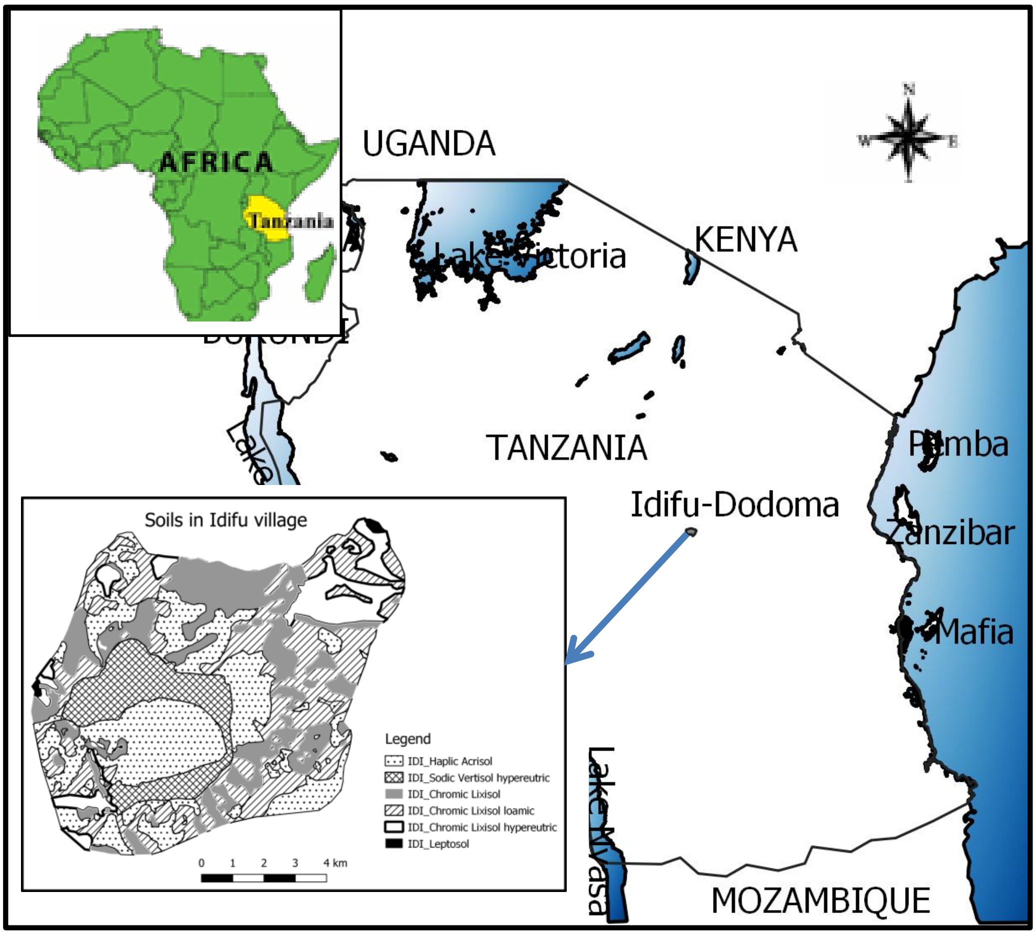

Figure 1. Location of the study site and soil distribution (Modified from [10]).

2.2. Description of the Experiment

Field experiments were conducted over four consecutive growing seasons (years), between 2014 and 2018. The seasons are abbreviated as 2014/2015 (SES1), 2015/2016 (SES2), 2016/2017 (SES3), and 2017/2018 (SES4). The rainy season (between onset and cessation) in the region typically occurs between October and the following May [26]. We define the onset date for the rainy season as the first rainy day with at least 5 mm of rainfall recorded (by any rain gauge within the study site) and with no dry spell of seven days occurring in the subsequent 30 days—a definition modified from literature [27,28] and based on farmers' and local experts' knowledge. The planting dates—determining the dates of which was a decision left solely to farmers—across all four seasons, were classified as early (any planting before 31 December); normal (planting between 1 and 20 January); or late (planting after 20 January). These groupings were based on the views of farmers participating in the experiment and the understanding of local experts gathered through discussions conducted during fieldwork. The experiments tested three different crop management aspects: (i) land preparation (flat cultivation (F) and tied ridges (TR)); (ii) fertility levels—i.e., no fertilization (NF) and microdosing fertilization (MD) (the application of 22 kg ha^{-1} diammonium phosphate (4 kg N ha^{-1}) with deep placement during planting, followed by 24 kg ha^{-1} urea (11 kg N ha^{-1}) three weeks after planting by top dressing); and (iii) planting dates (chosen by farmers as a measure of their reactions to variable rainfall patterns). The experiment layout was a completely randomized design with four treatments and farmers considered as replications.

The treatments were flat cultivation without microdosing (FNF)—which was used as a control—flat cultivation with microdosing (FMD), tied ridge cultivation without microdosing (TRNF) and tied ridge cultivation with microdosing (TRMD). Pearl millet was used as a test crop, with a planting density of 8000 plants/ha. Variable planting dates were used, as chosen by farmers.

The numbers of farmers participating in the experiments were 17 and 36—for SES1 and SES2 respectively—and 45 for both SES3 and SES4. Each farmer had four baby plots (the small farm plots—called baby plots, each with a size of 10 m × 10 m—were adopted by different farmers) making 68 and 144 baby plots for SES1 and SES2, respectively, and 180 baby plots for both SES3 and SES4. The farmers who were willing to conduct experiments in SES1 and SES2 were few and scattered across large distances. In SES3 and SES4, the number of farmers willing to conduct experiments increased due to an increased awareness. Therefore, additional farmers were merged with prior farmers to cover the entire village map (Figure 2a). To increase the accuracy and reliability of data collection, choices and allocation were done randomly using the k–means algorithm in an R package for spatial coverage sampling and random sampling from compact geographical strata was used (Figure 2a)—a method which is explained in detail in a previous study [10]. The final map showing rain gauge installation (Figure 2b) was an outcome produced after considering factors such as access, farmers' willingness, and the actual field conditions. A total of 38 rain gauges were concentrated in the rectangle to cover an area of 1500 ha of the Idifu village—where many farms are located (Figure 2b) in order to obtain high resolution data for yield and rainfall. The remaining 10 rain gauges were placed outside the rectangular area for collecting data from fields away from the centre of the village. The mapping (Figure 2b) was undertaken using the quantum geographic information system version 3.2 (QGIS 3.2, QGIS Development Team, Bonn, Germany). Therefore, a total of 48 rain gauge positions were identified, whereby 17 and 36 rain gauges were installed for SES1 and SES2 respectively, based on the number of participating farmers. A further 48 rain gauges were installed for both SES3 and SES4, based on the increased number of participating farmers. However, rain gauge positions 45, 46, and 47 (Figure 2b) were excluded from the final analysis due to accessibility.

All farmers who were participating in the experiments were trained on how to construct tied ridges and on the application of microdosing fertilization, since traditionally most of them only used flat cultivation without fertilization.

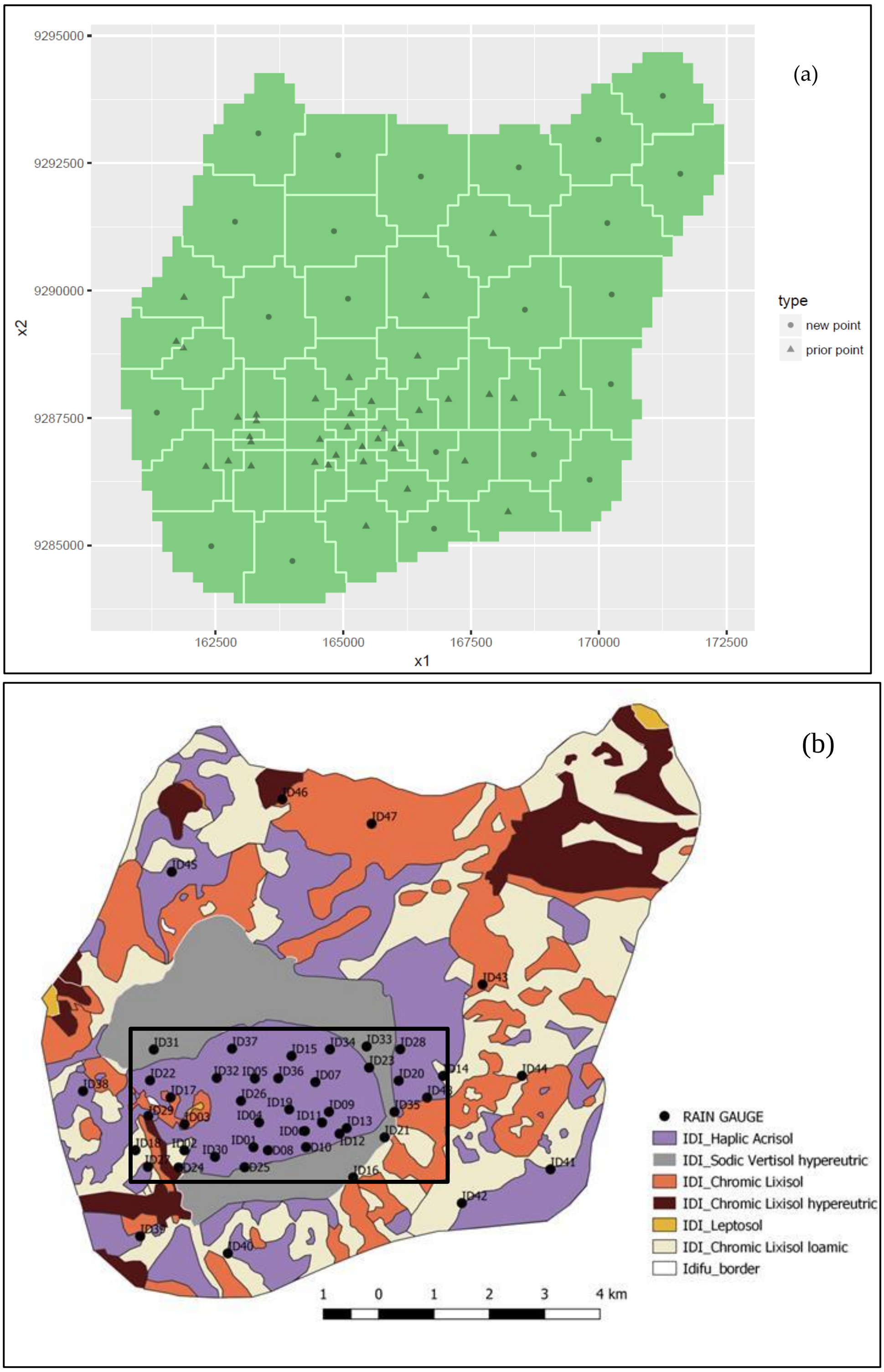

Figure 2. Rain gauges distribution representing the experimental design in Idifu village (**a**) initial design (**b**) final design after considering access and farmers' willingness (modified from [10]).

2.3. Data Collection

Daily rainfall data were collected using manual rain gauges, as explained by [10]. Topsoil characteristics for the area were analysed for physical and chemical properties, with average values and details provided in a previous study [25]. The planting dates and grain yield data during each season were collected by farmers under the close supervision of an agricultural field officer. The yield samples were taken to the laboratory for oven drying to obtain a dry weight (DW).

2.4. Calculations of Water Use Efficiency

Water use efficiency was calculated as a ratio of grain yield to the cumulative rainfall [29], as recorded by rain gauges (Equation (1)). This method of calculating WUE uses the gross amount of inflow—as explained by Molden [8] and supported by Perry [30]—and it accounts for consumed and non-consumed fractions of rainfall.

$$\mathrm{WUE}_i = \frac{Y_i}{CR_i} \quad (1)$$

where WUE_i is water use efficiency (kg mm^{-1}), Y_i is grain yield (kg), and CR_i is the cumulative rainfall (mm) at "ith" locations.

2.5. Data Analysis

Line charts, bar charts, and scatter plots were created using Microsoft Excel 10 (Microsoft Corporation, Redmond, WA, USA). The quantum geographic information system version 3.2 (QGIS 3.2, QGIS Development Team, Bonn, Germany) was used to map farmers and planting dates. Descriptive statistics (means, and standard deviations) were determined using Microsoft Excel for rainfall data and the yield of pearl millet during different treatments. The same procedures were adopted for standard deviations of spatial intra-seasonal onsets and intensities. ANOVA for intra- and inter-seasonal yields and WUE were conducted in R version 3.4.0 (R Core Team (2017), Vienna, Austria). We blocked the data to create homogenous blocks in terms of the planting window at early, normal, and late sowing dates. Blocking was performed as a means of improving the robustness of analysis, since individual planting dates can be more random yearly as compared to during the planting window. In case of significant differences at the 0.05 probability level, Holm's sequential Bonferroni post-hoc test correction for multiple comparisons of means was used to identify sample means that are different from each other [31]. The method is less conservative than the Bonferroni correction, but it provides an improved balance between the probability of making a Type I error and the probability of making a Type II error. Using Plotly online tools (Plotly Company, Montreal, Quebec, Canada) for data analytics and visualization, we created response surfaces to analyze the effects of treatments to intra- and inter-seasonal pearl millet yields.

3. Results

3.1. Rainfall Onset and the Distribution of Planting Dates

No spatial discrepancies in the onset of the rainy season existed for SES1, SES2, and SES4. Only SES3 exhibited a significant spatial variation of rain onset, ranging between 5 and 10 days. The average figures for inter-season cumulative rainfall during onset over the four seasons were 44.4 ± 8.5 mm, 40.6 ± 7.1, 11.7 ± 4.4 mm, and 11.5 ± 1.9 mm (mean ± SD) for SES1, SES2, SES3, and SES4 respectively. The average figures for seasonal spatial rainfall were 379.7 ± 19.8 mm (n = 17), 788.3 ± 22.0 mm (n = 36), 158.4 ± 24.8 mm (n = 45), 433.4 ± 42.2 mm (n = 45) (mean ± SD) for SES1, SES2, SES3, and SES4 respectively. The earliest onset was observed in SES2 (1 November, 2015), followed by SES1 (30 November 2014), SES3 (1 December, 2016) and SES4 (25 December, 2017). The planting dates (events) of farmers varied across space (Figure 3) and time. The average number of events per season was (7 ± 3), with planting dates differing regardless of the proximity between the fields (Figure 3). The highest number of events was 11 in SES2, while the three events in SES4 were the lowest. SES1 and SES3 demonstrated a difference of one day in terms of onset and their numbers of events were 6 and 8, respectively. Generally, events were concentrated between late December and January across all four seasons. Specifically, there were more events concentrated between 1 and 20 January, except for SES4, which exhibited an unusual trend which is explained by an excessive delay in seasonal onset.

The divergence of first planting dates from onset ranged between 1 and 36 days. The divergence was small when the onset was late (SES4) and large when the onset was early.

	Legend																										
Events	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	1	2	3
Sowing dates	02-Dec-14	14-Jan-15	15-Jan-15	16-Jan-15	19-Jan-15	07-Feb-15	01-Dec-15	23-Dec-15	24-Dec-15	05-Jan-16	06-Jan-16	09-Jan-16	11-Jan-16	12-Jan-16	22-Jan-16	23-Jan-16	02-Feb-16	15-Dec-16	04-Jan-17	05-Jan-17	09-Jan-17	10-Jan-17	13-Jan-17	16-Jan-17	19-Jan-17	26-Dec-17	27-Dec-17	02-Jan-18
Season	SES1						SES2											SES3								SES4		

Figure 3. The spatial distributions of farmers' planting events over the four seasons (the numbers in the map denote planting events for each season as presented in the legend).

3.2. The Effect of Planting Dates on Intra- and Inter-Seasonal Pearl Millet Yields and Water Use Efficiency

The farmers practiced early planting and normal planting more than late planting. As the onset for all four seasons occurred between November and late December, the planting dates reveal the preference of farmers to practice planting after onset in all seasons. Overall, the highest seasonal dry weight (DW) average yields were recorded in SES2 (782.9 kg DW ha^{-1}) followed by SES1 (711.4 kg DW ha^{-1}), and SES4 (682.0 kg DW ha^{-1}); the lowest average seasonal yield was recorded in SES3 (392.68 kg DW ha^{-1}) (Figure 4). Yields during SES1, SES2, and SES4 were not statistically different ($p < 0.05$) (Figure 5). Only SES3 was statistically significantly different from the rest ($p < 0.01$). A variability in seasonal rainfall was among the causes of discrepancies in average yield across the seasons, as noted in existing studies [10], however, the variable planting dates practiced by farmers were also a potential source of yield and WUE variations (Figure 4).

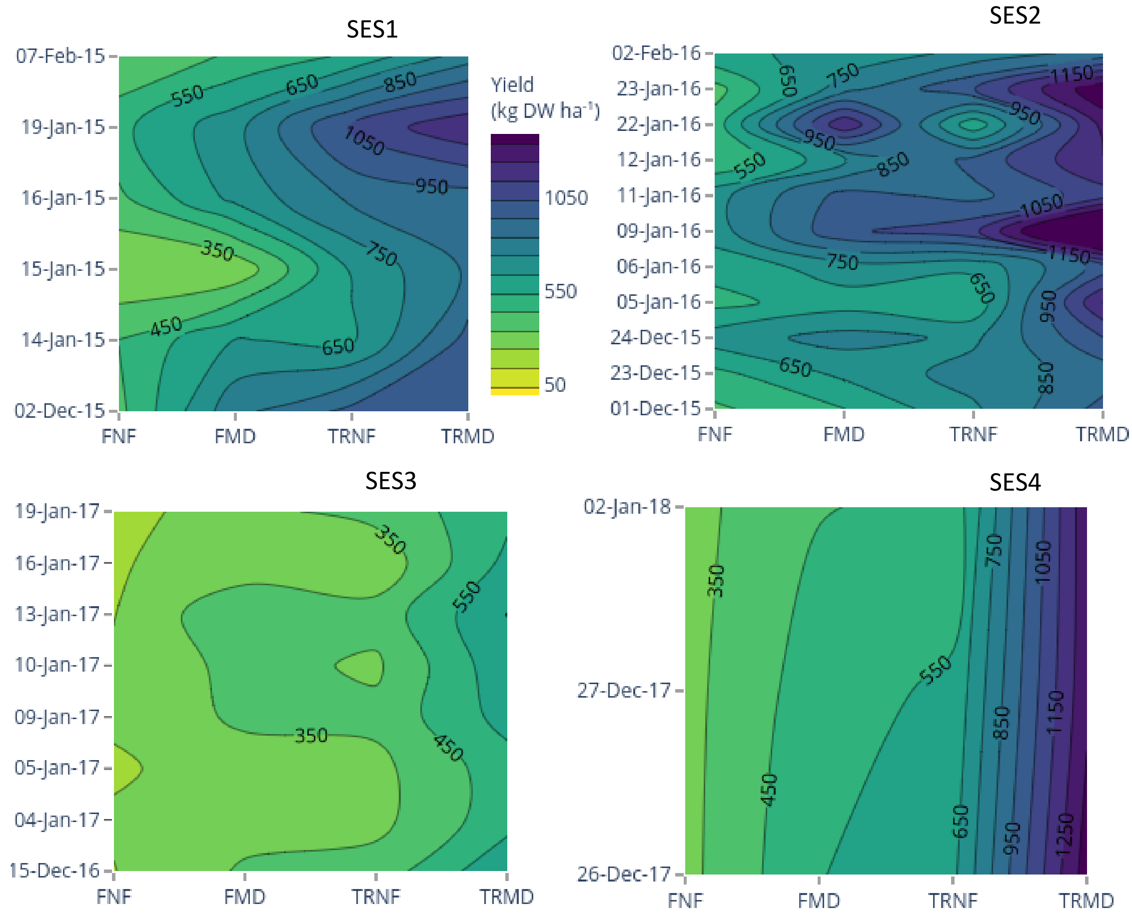

Figure 4. Pearl millet mean yields from the interaction between planting dates and treatments (the treatments (X-axis) are FNF, which denotes flat cultivation without microdosing; FMD, which denotes flat cultivation with microdosing; TRNF, which denotes tied ridge cultivation without microdosing; and TRMD, which denotes tied ridge cultivation with microdosing).

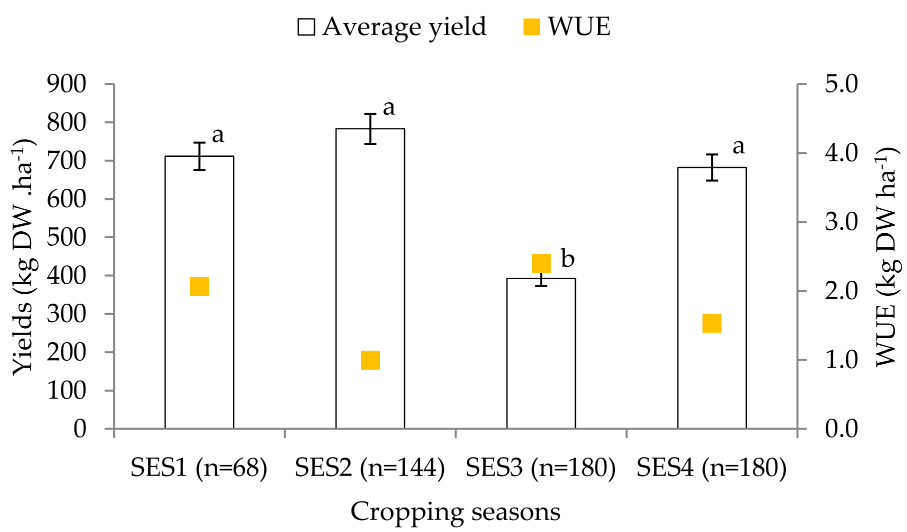

Figure 5. The pearl millet mean yields and water use efficiency (WUE) recorded for four seasons. The bars are percentage errors. Different letters indicate significant differences in pearl millet yield means at $p < 0.05$: Later analysed by Holm's sequential Bonferroni post-hoc test correction for multiple comparisons of means).

SES2 recorded the highest yield values; however, it was the poorest season in terms of inter-season water use efficiency (1.00 kg DW mm^{-1}) (Figure 5). Most of the seasonal rainfall was lost as runoff, deep percolation, or evaporation. The highest mean water use efficiency was in SES3 (2.39 kg DW mm^{-1}), followed by SES1 (2.07 kg DW mm^{-1}) and SES4 (1.53 kg DW mm^{-1}) (Figure 5). The lowest average WUE values in SES2 indicate the importance of rainwater harvesting and its storage possibilities during seasons with excess rainfall.

The intra-season average yields during early and late planting windows were statistically significantly different ($p < 0.05$) in SES1 and SES2. Normal and late planting in SES1 and early and normal planting in SES2 were not significantly different. During SES3 and SES4, farmers only used the early and normal planting windows, which did not result in significant yield differences. Average yields were predominantly higher as a result of early planting than normal and late planting, except for SES2 where higher yields were observed for the normal planting window (Figure 6). The reason for the unusual trend for intra-seasonal average yields in SES2 is the high cumulative seasonal rainfall (Figure 2) that exceeded crop water requirements. Late planting windows recorded the lowest average yields for both SES1 and SES2, demonstrating the risk associated with this practice. In addition, intra-seasonal mean water use efficiency values mimic yield patterns, with higher values during early planting windows than during normal or late planting windows, except for SES2. Water use efficiency values ranged between 0.53 kg DW mm^{-1} as a result of late planting in SES2 and 2.38 kg DW mm^{-1} as a result of early planting in SES3 (Figure 6).

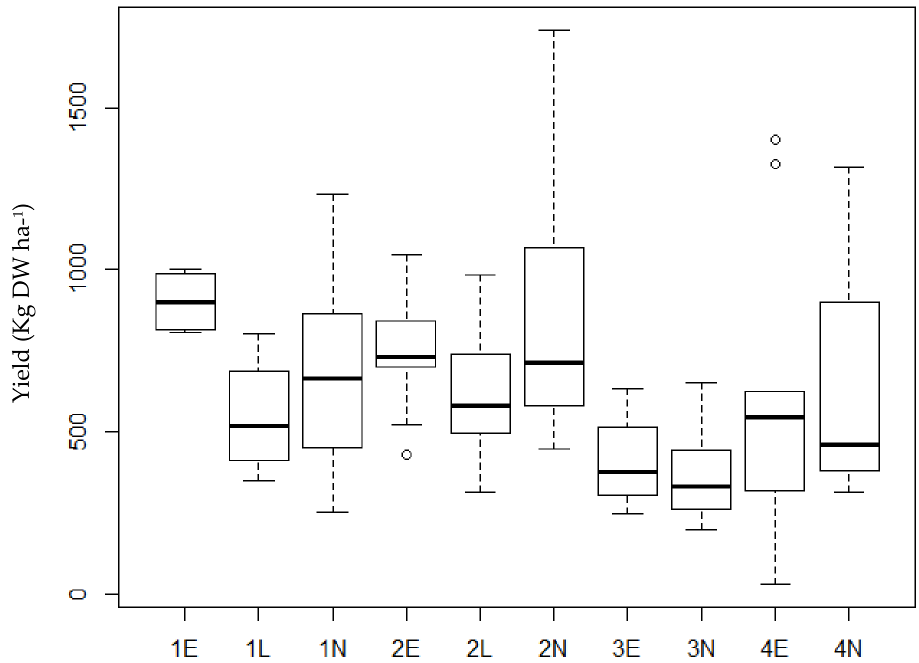

Figure 6. *Cont.*

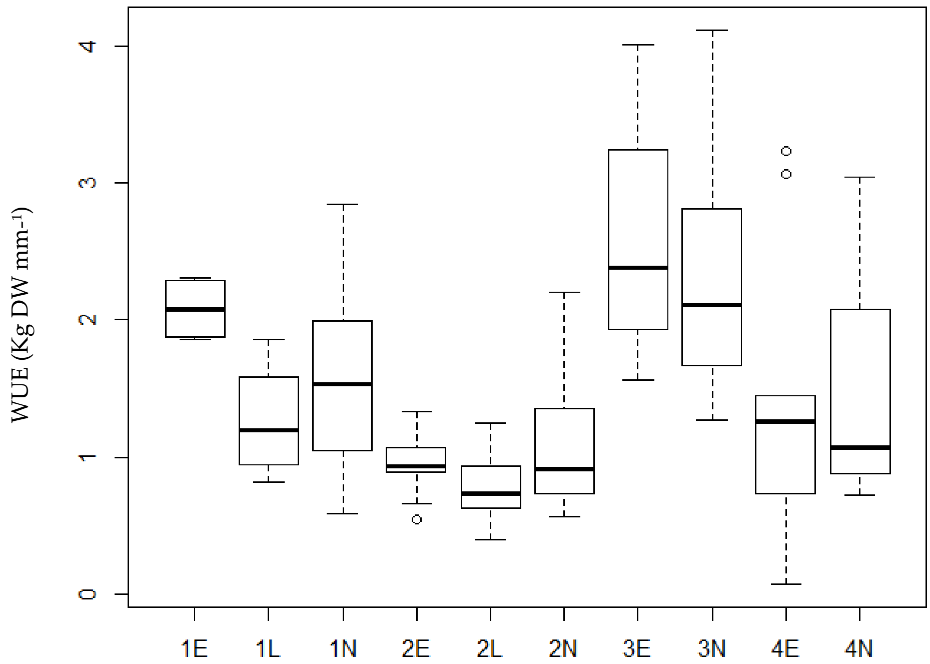

Figure 6. Pearl millet mean yields and water use efficiency (WUE) during different planting windows during cropping seasons (SES1 Early (1E) N = 32, Normal (1N) N = 24, Late (1L) N = 12; SES2 Early (2E) N = 36, Normal (2N) N = 88, Late (2L) N = 24; SES3 (3E) Early N = 16, Normal (3N) N = 164; SES4 Early (4E) N = 156, Normal (4N) N = 24).

3.3. The Interaction between Tied Ridges and Microdosing within Early, Normal, and Late Planting Windows and Its Effect on Pearl Millet Yield and Water Use Efficiency

The intra- and inter-seasonal average yields during FNF, FMD, TRNF, and TRMD were significantly different ($p < 0.05$) (Table 1). Microdosing was much more effective as a result of tied ridging when compared to flat cultivation. Seasonal average yields of pearl millet subjected to a combination of tied ridging and microdosing were higher than other treatments in all planting windows (Figure 7). This is because tied ridges prolonged soil moisture retention, thus allowing crops to use the nutrients efficiently.

Table 1. The interaction of tied ridges and microdosing with early, normal, and late planting windows and its effects on pearl millet yield for four seasons.

	Yields (kg DW ha^{-1})							
Treatments	**N**	**SES1**	**N**	**SES2**	**N**	**SES3**	**N**	**SES4**
FNF	17	393.2 a	36	576.2 a	45	252.9 a	45	318.3 a
FMD	17	650.0 b	36	720.9 b	45	370.3 b	45	504.8 b
TRNF	17	847.8 c	36	717.8 bc	45	344.7 bc	45	567.4 bc
TRMD	17	954.7 d	36	1116.7 d	45	602.5 d	45	1337.4 d

Mean yields followed with the same letter in the same column are not statistically significantly different (ANOVA $p \leq 0.05$/Holm's sequential Bonferroni post-hoc test). N is the number of samples for each treatment; FNF denotes flat cultivation without microdosing; FMD denotes flat cultivation with microdosing; TRNF denotes tied ridge cultivation without microdosing; and TRMD denotes tied ridge cultivation with microdosing).

Similarly, the WUE was higher under TRMD in all seasons, with early planting recording higher values than normal or late season planting. The spatial average values for WUE were 2.07 ± 0.76 kg DW mm^{-1}, 1.00 ± 0.28 kg DW mm^{-1}, 2.39 ± 0.86 kg DW mm^{-1}, and 1.53 ± 0.98 kg DW mm^{-1} for SES1, SES2, SES3 and SES4 respectively. SES3 recorded the highest WUE values followed by SES1, SES4 and SES2 (Figure 7). In SES2, the WUE in TRMD during the normal planting window was higher than the WUE for both early and late planting. The highest achieved value of WUE was 3.8 kg DW mm^{-1}

(0.38 kg m^{-3}) in SES3 under TRMD and the lowest recorded WUE was 0.53 kg DW mm^{-1} (0.05 kg m^{-3}) in SES2 under FNF. In all seasons, TRMD improved the WUE with a greater effect as compared to other treatments (Figure 7). Early and normal planting produced higher values of WUE than late planting for SES1 and SES2.

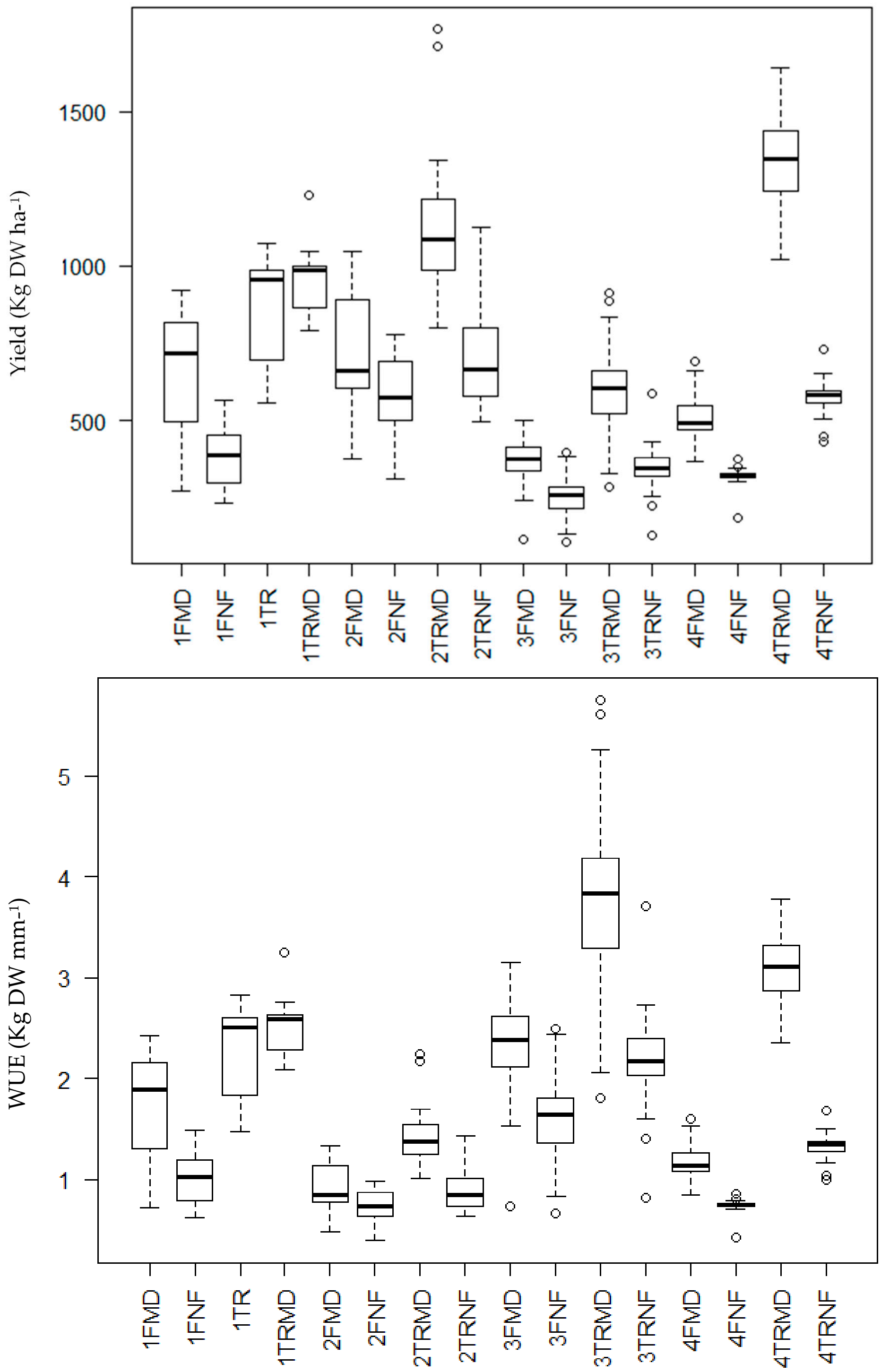

Figure 7. The intra- and inter-seasonal average pearl millet yields under different treatments and planting windows across four cropping seasons. The treatments (X-axis) are FNF, which denotes flat cultivation without microdosing; FMD, which denotes flat cultivation with microdosing; TRNF, which denotes tied ridge cultivation without microdosing; and TRMD, which denotes tied ridge cultivation with microdosing).

4. Discussion

Variable rainfall patterns impose great challenges to planting operations in semi-arid SSA. The rainy season onset and its intensity, along with cumulative seasonal rainfall variation, cause production uncertainties. During the four seasons, these factors varied widely at the study site, both across space and time. This is consistent with findings made by the authors of [11,12]. Farmers cope by varying planting dates (Figures 3 and 4), which fall during different planting windows (early, normal and late planting windows) (Figure 7) that are also associated with different challenges. For instance, previous studies indicate that late sowing results in lower yields due to a limited time for plant growth [12,32]. Similarly, we found that late planting produced lower yields than normal and early planting, while higher yields were predominantly achieved during the early planting window (Figure 6). The authors of [33] suggest that if weather forecasts predict higher than average precipitation, then farmers should concentrate on the normal planting window, as it results in higher yields. Our findings for SES2 (Figure 6) are consistent with this, as this season exhibited relatively high yields during the normal planting window. Consequently, excessive rainfall may interfere with the normal growth of crops if planting is done very early, affecting crop yields [34–37].

When farmers decide to plant, the decision depends on the intensity of the rainfall onset. If intensity is high (greater than 50 mm), farmers expect a reliably rainy season, thus triggering early planting, as in SES1 and SES2 (Figure 6). The confidence gained from early planting also stimulates a wider planting window that extends to late planting. High initial rainfall is associated with higher average season yields because the soils are brought to moisture field capacity, or near it, much earlier. This provides sufficient soil moisture, an environmental condition that supports the germination and growth of plants. Conversely, a small amount of onset rainfall (i.e., less than 20mm [27]), pushes back planting decisions, as farmers are less confident of a good rainy season. However, our field observations suggest that if the rain season onset is delayed, then planting operations are concentrated on a few days following rainfall; thus, farmers are pressured to take advantage of a narrow planting window as the chance of losing the entire season's harvest increases. Consequently, yield variations were minimal during the narrow planting window as compared to wider planting windows, meaning that the chances of losing or obtaining a good seasonal yield are almost equivalent to the narrow planting window. The authors of [38] indicate that an early onset is highly associated with a longer growing season, which is in line with our findings (Figures 3 and 4). Higher yields are also produced during early onset and wider planting windows. Possible reasons include farmers having enough and/or repeated time to prepare the fields as compared to when the onset is late. Additionally, in cases of poor germination, farmers have an opportunity to re-sow the crops and increase the number of plants per hectare. A wider planting window increases the chance of harvesting certain plots, even if the rainfall distribution is not very good, as the likelihood that at least one planting event will align with seasonal distribution increases. Furthermore, a wider planting window also provides the flexibility of practicing scattered plots [4,10]. The optimum planting time may be further explored by using crop models [24].

Water use efficiency values are generally lower in SSA than in other regions of the world, despite substantial efforts to increase crop per drop of water in both irrigation and rainfed agriculture [9]. Very low values are found in semi-arid regions where water scarcity is a major challenge. This study also found very low values of WUE (Figures 5–7). The values of WUE found in this study under flat cultivation and non-fertilized treatments demonstrate the need to regularly encourage farmers to apply methods that improve yield and WUE. The within-season WUE improvement is important, since it shows the actual improvement that is achievable. Consequently, intra-seasonal improvement can be reflected in the inter-season comparison (Figure 7). In this study, the use of tied ridging was vital for the efficient use of limited seasonal precipitation (Figure 7). In SSA, where both soils and rainfall are the limiting agricultural production factors, the use of tied ridges and microdosing is the premier approach for improving both yields and WUE values (Figure 7). The ability of tied ridges to prolong moisture retention [10,39,40] helps crops utilize the provided microdosing, thus enhancing growth and yields, especially if a short dry spell occurs during the season. This study demonstrates that using TRMD can improve WUE for low-income small holder farmers by up to more than three times current values (Figure 7). Even with sufficient rainfall, lower yields are achieved under flat cultivation (a practice common to many farmers) than with the use of tied ridges—a finding reported consistently [9,41–43], which subsequently lowers WUE values. Therefore, farmers should adopt tied ridge cultivation with microdosing in order to enhance yields and water use efficiency. The challenge of labour requirements may be the next concern to address, especially for the design of machine implements that can make it easier to cultivate tied ridges.

This study is limited by consistency in the setup, in terms of the number of participating farmers for each season. In the first two seasons, the number of farmers was not the same, thus, variations in yield data may be caused by both the spatial variations of farmer locations and the number of farmers involved. The design of farmer choices in SES3 and SES4 was consistent. Although many farmers sought to participate, the analysis maintained a consistent number of farmers and plots. Additionally, the varying number of participating farmers was a result of farmers' initial reluctance to join the study. Thus, higher resolution data were collected in SES3 and SES4 than in SES1 and SES2. We can generally state that, in research where farmers are directly involved in the decisions, variations are inevitable. As in this case study, where farmers were given an overall mandate to decide on when to plant, the data set of planting events was not uniformly distributed in all seasons. It was clear that even neighbouring fields fell during different planting dates and windows. Since farmer planting dates varied widely for inter-seasonal comparison and its distribution was not uniform for intra-seasonal analysis, grouping the data into early, normal, and late planting windows resulted in a robust output that can be re-evaluated. This grouping approach was a modification of a previous study [38] that provided a meaningful interpretation of the expected outputs when dealing directly with local innovations or improvements in crop management strategies.

5. Conclusions

In SSA, the rainy season onset varies widely, as do the planting dates, which affects yields significantly both within and between seasons. An early onset of the rainy season prompts farmers to start early planting, with a wider planting window, while a late onset prompts farmers to plant immediately, concentrating their planting efforts into a narrow window. Wider planting windows resulted in high yields with higher variability than did narrow windows. Similarly, early planting resulted in higher yields and WUE values versus normal and late plantings, except when there was excessive rainfall. Microdose fertilization increased both the yield and WUE of pearl millet significantly, with a higher effect exhibited during tied ridging than under flat cultivation. The use of tied ridges with microdosing during early planting is an effective solution when low-income smallholder farmers in semi-arid agro-climates face spatiotemporal rainfall variability and poor soils; thus, it is one of our recommendations. A more detailed evaluation of optimal planting dates is possible with modelling approaches—an avenue recommended for future research.

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