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Application of AquaCrop Model Yield Optimization for Prediction of Optimal Sowing Dates under Alternative Soil Moisture Regimes in Laikipia, Kenya.

Mutonga, M.W[1], Kipkorir, E.C[2], Ng'etich, W.K[3].

[1]Kirinyaga University, KENYA [2]Moi University, KENYA[3]University of Eldoret, KENYA

Correspondence: *mmutonga@kyu.ac.ke*

Abstract

This study presents the use of AquaCrop model in predicting optimal onset dates for wheat crop grown under ASAL conditions in Laikipia County, Kenya. Modeling of onset dates was done through simulation of root zone moisture content to reduce yield losses from crop failure. The optimal sowing date(s) for rain-fed wheat was based on AquaCrop rainfall criterion for generation of onset dates and optimization analysis of AquaCrop simulated grain yields. Cumulative rainfall of 10 mm in 4 successive days' onset criteria equivalent to the calculated Readily Available Water (RAW) required at 10 cm soil depth was adopted. Based on the onset criteria, a total of 57 simulations (19 years rainfall record and three onsets: early, normal and wet) was run using AquaCrop model and frequency analysis applied to the simulated yields to get the yield levels expected at varying levels of probability of exceedance. The set threshold was incremental at 0.5 ton/ha level from 0-12 ton/ha. The probability of exceedance was zero for threshold mean yields beyond 5.5, 11.0, 11.5 ton/ha for early (SD1), normal (SD2) and late (SD3) onset respectively. At 20%, 50% and 80% probability of exceedance, the average expected yield was less or equal to 4.5, 0.5 and 0.38 ton/ha for SD1, 4.5, 0.75 and 0.38 ton/ha for SD2 and 6.0,0.75, 0.38 ton/ha for SD3 respectively. Results indicated that zero tillage optimized the yield in all the sowing dates selected. In conventional tillage, early onset had high yield advantage for the viable early onset, but the risk of failure was high representing 22.11%. It is recommended that sowing date, which is a technology problem, be given a lot of attention.

Received: July 25,2022
Accepted: 26 Sep 2022

Published: 9th Nov 2022

Keywords: *Optimization Analysis, Staggering Onset Dates, Frequency Analysis, Zero Tillage, Climate Change.*

Introduction

Prediction of sowing dates have been done using science and religious cum traditional methods like Ramadhan (Ati *et al.*, 2002), the use of plant phenology such as flowering of the Acacia trees that mark the end of a dry period (Sekhwela and Yates, 2007), use of accumulated rainfall totals using the Walter's and Sivakumar's method (Ati *et al.,* 2002; Sivakumar, 1988), use of rainfall evaporation method, and historical analogues approach (Hansen and Indeje, 2013). These approaches have varied levels of accuracy, often characterized by yield losses. While traditional methods reportedly perform poorly, the other methods are not without challenges. Walter's method predicts quite early onset, while Sivakumar's predicts late onsets (Ati *et al.*, 2002). Similarly, the use of plant phenology is threatened by deforestation and depletion of indigenous species.

Although the scientific methods are fairly reliable, there are other constraints which affect accuracy of predicting onset of sowing dates especially in arid and semi-arid areas (ASAL). Climate change is a major threat to accuracy of predicting onset of sowing dates (FAO, 2015). Most agricultural production takes place in an environments with risks and uncertainties especially in ASAL areas where water supply to crops from rainfall is variable and unreliable (Fereres *et al.,* 2007). According to Onyari *et al*., (2010), ASAL areas are characterized by temporal and spatial variability of rainfall. The rainfall is usually low and unreliable limiting productivity (Wamari *et al*., 2012). As a result, the timing and relative lengths of each crop growing period vary substantially with location (Mujdeci *et al*., 2010) and this leads to reduction in yields by up to 75% (Barron *et al*., 2003).

Further, most rain-fed farmers depend on hired agricultural machinery which also contributes to delay in land preparation. This overdependence on contracted agricultural machinery among other factors further cause delay in sowing (Monroy *et al*., 2013). However, even when the machines are available, other constraints among them land sizes, machine breakdowns, labor availability often hinder farmers from sowing their entire crop at the first onset of sowing period (Mhizha, 2010). Mhizha, (2010) recommended staggering the sowing dates to accommodate the above challenges and other uncertainties (Raes *et al.*, 2004) which are difficult to predict or control.

Modeling of onset dates through simulation of root zone moisture content can be used to reduce uncertainty and manage risks of crop failure from a false start of the sowing period or delayed sowing which significantly shortens the growing period. If properly modeled, initial soil water (left over from the previous season) can influence early establishment of the crop and contribute to water use and yield later in the season, particularly in low rainfall seasons (Kipkorir *et al*, 2007).

Laikipia County is among the main wheat growing regions and falls under ASAL area of Kenya whose seasonal rainfall according to Huho *et al.*, (2012) has been marked by delayed onsets, declining number of rain days and increased intensities altering farming calendars with negative impact on the yields. To increase and sustain production in this area, improvement in farm management practices, soil and water conservation, farming systems and timely sowing from weather prediction need to be encouraged.

In this study we used the AquaCrop model (Asseng *et al.*, 2008) to generate onset dates by appraising the rainfall data file for the region. Rainfall data consideration was best suited for this rain-fed farming where sowing onset is determined by rainfall event(s). Optimal sowing time corresponds to adequate soil water content at the root zone to support crop growth. This is what was simulated to determine and generate the sowing dates with low risk of failure.

Materials and Methods

Optimization analysis was applied to obtain the algorithm that allocates the best acreage proportion to the generated sowing dates for maximum total yield taking care of the mentioned constraints over the simulation period. Microsoft Excel Solver® tool was used for optimization analysis of simulated yields.

Study area

According to Mutonga *et al.,* (2019) Laikipia County is characterized by the ASAL climatic conditions despite being a major potential grain producer. The area receives mean annual rainfall of 650 mm per year, but often very unreliable with the onset of the rains highly variable and can be delayed by up to two months in some seasons (Ojwang' *et al.*, 2010).

Experimental site and design

The study was carried out in Lengetia farm in Laikipia County. The farm of approximately 4500 acres in area is located in a wheat growing zone, and has been under zero tillage for more than ten years and the dominant soil texture in the farm is clay soil (Mutonga *et al.,* 2019).

The field trial was laid out in randomized complete block design in split plot arrangement during the short rain season of 2015/2016. Tillage treatment formed the main block factors in the split plots (zero tillage (ZT) and conventional tillage (CT)), while sowing dates representing the early (SD1), normal (SD2) and late sowing (SD3) onsets (Table 1) formed the sub-plot factors randomized and replicated thrice on each of the split plot.

Table 1: Sowing dates representing the three sowing season characteristics determined by onset of rainfall an adjustment of rainfall criterion in AquaCrop (Raes *et al.*, 2004, Raes *et al.*, 2012).

Sowing Date	Occurrence	Symbol	Sowing time Characteristic	
			Onset time	Type of sowing
29th September	1st	SD1	Early	Dry
21st October	2nd	SD2	Normal	Wet
21st October	2nd	WTSD2	Normal (irrigated)	Wet
31st October	3rd	SD3	Late	Wet

Generation of onset dates

Sowing dates were determined using the onset of rainfall and rainfall depth criterion in AquaCrop model using historic daily rainfall data (Raes *et al.*, 2004, Raes *et al.*, 2012) (Table 1). Generation of the onset of growing period using AquaCrop Model was based on historical farmer's practice of sowing (to establish the normal (wet) planting date and sowing window), historical climatic data and criteria for selection of dry sowing date(s) by the AquaCrop Model based on 19 years' historical rainfall data. The onset dates were generated based on soil moisture at the root zone to match the requirement for wheat to germinate.

The Raes *et al.*, (2004) rainfall criterion was used with little adjustment because the accumulated rainfall of 40 mm was limited under ASAL climate. The adjustment was that germination was triggered by received rainfall of at least 10 mm for four consecutive days. This is the amount of rainfall that was required to raise the soil water content at wilting point to field capacity in a profile of 10 cm of the top soil. This was based on the calculation of Readily Available Water (RAW) from the analysis of sampled soil. Also considering that there was stored soil water from zero tillage practice over the years, this rainfall was sufficient to trigger germination and the stored soil water would support crop growth until the next rainfall event was received.

A soil water balance analysis by the AquaCrop model and yield simulation was used to determine whether the generated date was a false start based on yield and risk of failure of the crop after germination. The soil moisture content was the limiting factor and therefore the rainfall criterion was preferred.

The historic daily maximum and minimum temperature data for the region was used as input file in AquaCrop model when generating initial onset dates and for scenario analysis. This was meant to take into consideration the temperature effect of the project site. To achieve calibration and validation of the AquaCrop Model for the local condition, a temporary weather station was set up equipped with a maximum and minimum thermometer for measuring the daily temperatures and data collaborated with those obtained from Lamuria Weather Station approximately about 1.5 km from the project site. Temperature was assumed to have a direct effect on soil water content through evaporation and was assumed to vary substantially with variation in tillage practice and therefore captured when monitoring the root zone soil moisture content (Mutonga *et al.,* 2019).

From experience, the farmers sowing window lies between 15th September and 15th October of every calendar year. The search window in AquaCrop was stretched by fifteen days on both sides to between 1st September and 31st October to take care of probabilities of early onset or very late onset of rainfall which trigger the onset of sowing. The first date to be generated within the search window comprised the early (dry onset date) while the first generated onset date after seven days from early sowing represented the normal sowing date. Finally, the first generated date after seven days from the normal sowing date was considered as the late sowing date.

The four sowing onset dates (Table 1), representing the three onset dates under rain-fed condition, and one water regime control treatment (with supplemental irrigation) were randomized among the subplots as; one dry onset (sowing date one-SD1), one normal onset (sowing date two- SD2), one late onset (sowing date three-SD3) and one normal onset under supplemental irrigation (water regime treatment - WTSD2). The effect of rain days was not investigated because it was assumed that rainfall had a uniform and direct effect of raising the soil water content in the root zone and was the sole source of water for rain-fed trials.

The sub-plots were 24 m^2 (4 m × 6 m) each and consisted of 12 rows, 6 m long and 0.3 m between rows, separated by 1.5 m to ensure that the treatments in the plots were independent of each other. The total number of sub-plots was 24: two tillage treatments (ZT and CT (2TT)), by four onset-dates treatments (4SD) replicated thrice (3) i.e. (2TT × 4SD × 3=24). The control treatment (WTSD2) in both the conventional and zero tilled plots was meant for calibration of the AquaCrop model, while the remaining trials were for validating the model.

Optimization analysis

Optimization analysis on the simulated yield results for every year and for different generated planting dates over the 19 years of available historic daily climate data was applied to obtain the optimal allocation of acreage to the various sowing treatments with the best maximum yields every year. This was achieved using Microsoft Excel Solver Tool and simulated yields in validated AquaCrop model.

For purposes of developing the optimization objective function, a total yield term (Y_T) was defined as the weighed summation of the grain yield simulated for each of the three sowing options for each year and over 19 years of available historic data (Equation 2.4.1)

$$\boldsymbol{Y_T = \sum_{s=1}^{3}(A_i\, Y_{S_i})} \qquad \textbf{(Eqn 2.4.1)}$$

The aim was to maximize mean grain yield for all the 19 years (Equation 2.4.2) (Mhizha, 2010). Therefore, the objective function which formed the target cell was;

$$\mathbf{max} \sum_{\mathbf{j=1}}^{\mathbf{N}}(\mathbf{Y_T/n}) \qquad \textbf{(Eqn 2.4.2)}$$

$$for\ j = 1\ to\ N$$

Subject to constrain on area; $0 \le A_i \le A$ and

$$A_1 + A_2 + A_3 \le A$$

$$for\ i = 1,2,3$$

Constraints on the changing cell; $0 \le A_1 \le 0.4A$

$$0 \le A_2 \le 0.6A$$

$$0 \le A_3 \le 0.6A$$

The values, 0.4, 0.6 and 0.6 are the weight factors corresponding to 25%, 37.5% and 37.5% proportional area allocation recommended for the early, normal and late sowing dates respectively. This was obtained from expected target yields and frequency of failure at 50% probability of exceedance.

Where,

$S_{i,}$ is the respective simulated onset date (i.e. SD1, SD2 and SD3 representing the early, normal and late season onset), for i=1, 2, 3; Y_s, is the simulated grain yield of the S^{th} sowing date (ton/ha); $A_{i,}$ is a weighted factor, a proportion of area (acreage) allocated through optimization to sowing date $S_{i.}$

A, is the total area (unit or 100%) to be considered and allocated to the three sowing seasons based on the proportions obtained in the frequency analysis while, N, is the total number of years of simulated yield considered in the optimization (based on available historic climate data, 19 years). The A_i weighted factor given to each yield term in the summation was aimed at allocating more land to desirable treatments and less (or even none) to undesirable treatments not likely to contribute positively to average yield.

Thus, the weighting factor formed the changing cells of the optimization procedure while the target cell was the mean of total yield (Y_T/n) over the 19 years. The target cell was maximized for highest stable yields (Equation 2.4.2). By means of constraints, the number of options selected in the optimization was restricted.

Data analysis

Frequency analysis and homogeneity test using RAINBOW was applied to secondary climate data and simulated yield data to check and ensure that they belonged to the same statistical population (Raes *et al.,* 1996*;* Raes *et al*., 2006). Additionally, the Excel spreadsheet (windows 2007) and SPSS statistical software (Version 20) were used for tabulation, descriptive statistics and graphical representations.

Results

Yield as a function of tillage

Zero tillage plots had significantly high yields at $p<0.05$ than conventional tillage for all the rain-fed sowing treatments. The respective mean grain yield in both tillage treatments and varied sowing dates are presented on Table 2.

It is apparent that all the onsets in zero tillage yielded higher with a mean grain yield of 8.69 ± 0.54 ton/ha for the rain-fed trials which was above the plant breeders target yield of 8.5 ton/ha as compared to 5.70 ± 1.08 in conventional tillage (Table 2). The variation in mean grain yield for conventionally tilled rain-fed trials and the varied sowing dates was higher than that of zero tillage under the rain-fed trials (Table 2). This affirms the effect of sowing dates on grain yield and the need for accurate prediction of sowing time and confirms the effect of zero tillage in enhancing high grain yields (Mutonga *et al*., 2019).

Table 2: Analysis of the wheat grain yields for the two tillage practices under the four sowing onset dates.

	Independent variables Mean Yield ton/ha		Levene's Test for Equality of Variance		T-Test for Equality of means		
Onset date	ZT	CT	F	Sig.	T	$LSD_{0.05}$	St.dev
SD1	8.21	4.196	1.30	0.32	8.50	0.001	2.84
SD2	8.41	6.681	3.08	0.15	1.98	0.118	1.23
SD3	9.45	6.226	0.12	0.75	18.62	0.000	2.28
WTSD2	12.92	13.607	6.35	0.07	-0.83	0.453	2.12
Mean	9.75 (8.69)	7.68 (5.70)	**KEY** CT-conventional tillage				
St.dev	1.95 (0.54)	3.66 (1.08)	ZT-zero tillage SD1,2,3-Sowing dates one, two & three respectively WTSD2 –water regime treatment ( )-mean yield and standard deviation under rain-fed condition				

Similarly, the variation of yield between the two tillage treatments under similar sowing dates was high both for the early onset and late onset. This variation is relevant and also serves as an indicator of the effectiveness of zero tillage practice coupled with proper timing of the sowing onset dates. Further analysis of the grain yield result indicated that, farmers practicing conventional tillage are likely to produce less than the target yield of 8.5 ton/ha by 50.64%, 21.4% and 26.75% respectively for early, normal and late sowing, while those practicing zero tillage, the deviation from the mean target yield is not significant ($p<0.05$).

Using the field results of the water regime trial plots (WTSD2), the AquaCrop model was satisfactorily calibrated and validated under conventional tillage but was not satisfactory in zero tillage (Calibration details not discussed in this paper). This limited the application of the AquaCrop model only to the conventional tillage. However, as evident from the grain yield results for the three rain-fed onset dates, the yields were above the target yield, without a significant variation between them (Table 2). It is therefore apparent that, zero tillage had optimized the sowing onsets and all the dates falling within the sowing window were considered appropriate and optimal. That means, zero tillage practice as a soil and water conservation practice, can be used to support staggering strategy without significant yield variations.

Generated onset dates

The 40 mm in 4 successive days' criterion (Raes *et al.,* 2004) was very severe generating only one sowing date in some years while in some no onset within the sowing window. An attempt to use the less strict AREX criterion (25 mm in 7 days but with longer period of 10 days instead) (Raes *et al.,* 2004), was not successful because it also generated very few days (at most two and in some years none) occurring either too early or too late in the season. The two conditions could not be met for this ASAL region and therefore it was relaxed to 10 mm in 4 successive days. This was based on the calculation of Readily Available Water (RAW) (6.7 mm up scaled to 10 mm to cater for any losses) at 10 cm soil depth and through the observation during the experiment (the received rainfall which germinated the seed for SD1 was 8.8 mm which was less by 1.2 mm). The generated onsets were selected based on their occurrence as SD1, SD2 and SD3 representing the early, normal and late season as presented in Table 3.

Table 3: Average sowing date occurrence determined by the relaxed rainfall depth criterion.

	Characterized season onset dates		
Number of onsets	Early Onset	Normal Onset	Late Onset
1	6-Sep	4-Oct	15-Oct
2	8-Sep	5-Oct	17-Oct
3	10-Sep	6-Oct	19-Oct
4	14-Sep	8-Oct	20-Oct
5	20-Sep	10-Oct	26-Oct
6	30-Sep	14-Oct	31-Oct

The result of multiple yield simulation with the generated dates was then subjected to frequency analysis.

Frequency analysis of simulated yields

Frequency analysis was performed to give insight on how often the simulated yield was below the threshold yield (frequency of failure). Considering the model parameters specified for each season, 3 sowing onsets; early onset, normal onset and late onset for the 19 years of historic climate data, a total of 57 simulations was run. A frequency analysis using Microsoft Solver tool was applied to the simulated data to determine the yield levels expected at varying levels of probability of exceedance and with a set threshold incremental at 0.5 ton/ha level from 0 yield to maximum 12 ton/ha as presented in Figure 1. Beyond a threshold mean yield of 5.5 ton/ha, the probability of exceedance is zero percent for SD1, zero percent for threshold mean yield of 11 ton/ha for SD3 and zero% for mean yield greater or equal to 11.5 ton/ha for SD2 (Figure 1).

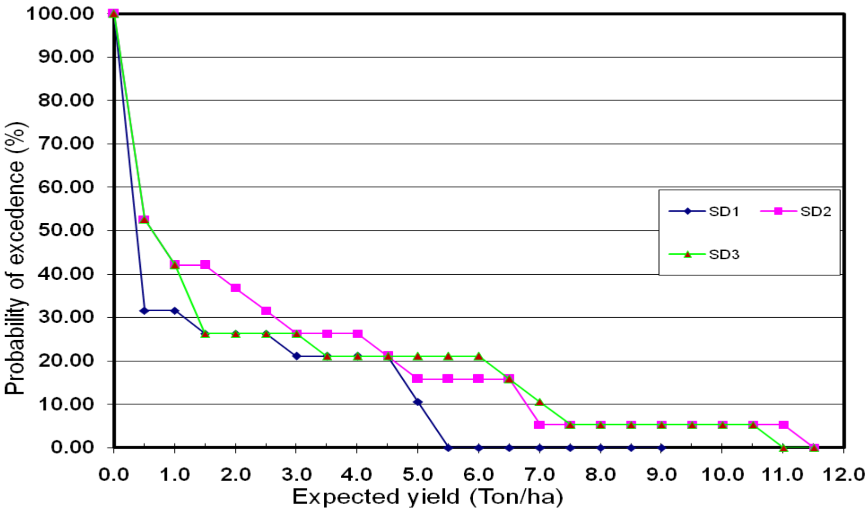

Figure 1: Probability of exceedance of wheat specified by planting dates (SD1, SD2 & SD3) obtained using validated AquaCrop model.

Further analysis of failure rate results indicated that early onset had the highest failure rate followed by the late and finally the normal. The Early onset had a high yield advantage for the viable early onset as compared to both the normal and the late onset only that the risk of failure of such onsets was high.

Similarly, in years without an early onset, the normal onsets had higher yield advantage than the late. Results also demonstrate a high failure rate for the early onset and late onsets as compared to normal onset depending on the characteristic of the rainfall in the season and not the occurrence, that is, neither too early nor too late into the season but the general wetness of the season.

At 20%, 50% and 80% probability of exceedance, the average expected yield was less or equal to 4.5, 0.5 and 0.38 ton/ha for the early onset (SD1), 4.5, 0.75 and 0.38 ton/ha for the normal (SD2) and 6,0.75, 0.38 ton/ha (SD3) respectively (Figure 1 and Table 4).

Table 4: Expected yields (ton/ha) for specified probability of exceedance

Probability of exceedance		Expected yield (ton/ha)	
(%)	Early Onset	Normal onset	Late onset
20	4.5	4.5	6.0
50	0.5	0.75	0.75
80	0.38	0.38	0.38

The 20%, 50% and 80% probability of exceedance can also be linked to probability of a season being wet, normal and dry respectively with respect to received rainfall.

Optimization analysis

Due to the prevailing constraints in wheat production and the need to stagger the sowing dates to minimize the constraints such as labor resources availability and land size, optimization analysis was carried out aimed at allocating the maximum possible acreage proportion to the dates with the best yields. The idea of failure rate was applied at 50% probability of exceedance (considered as the normal or average) such that the normal onset and the late onsets were set to receive 37.5% of the acreage each with the early set to receive 25% due to the high risk of failure associated with it (Figure 2).

The maximized mean grain yield results of optimization allocated 12.63% to the early, 34.74% to the normal and 30.53% to the late onset (Figure 3). This accounted to 77.89% of the total area to be sown with the remaining 22.11% not allocated due to the nature of the season with only two or one onset and the constraint on land size. This 22.11% could also represent a false start of the sowing period, where the crop germinates but does not get to full maturity because of low or no rainfall later in the season.

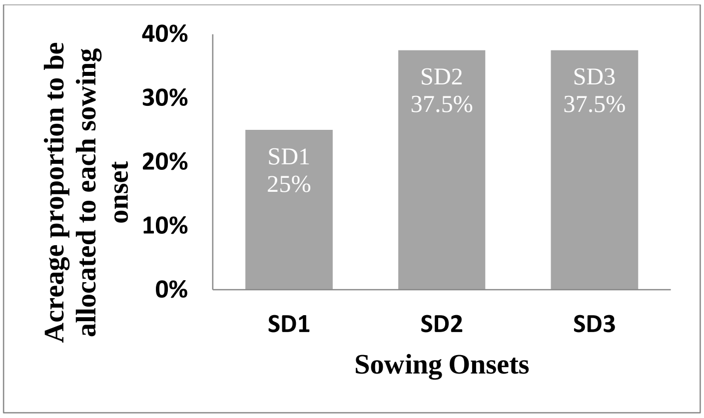

Figure 2: Bar graph representing the area to be allocated to each sowing onset based on Land size constraint (Weighed factor) at 50% probability of exceedance.

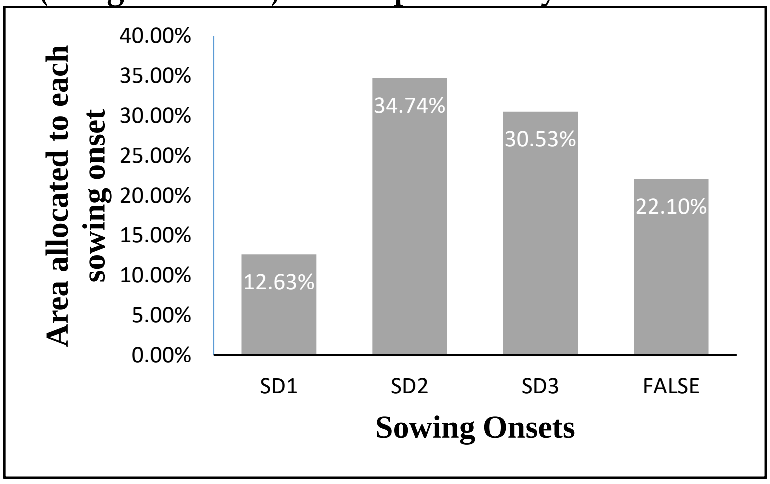

Figure 3: Bar graph representing the optimal sowing strategy (area allocation) indicating the possibility of false start after performing the optimization analysis based on simulated yield.

The farmers in Laikipia County, should through aim at doing most of their sowing during the 1st -14th of October under the normal season proportional to 34.74% of their total land area, 12.63% of the land area between 1st-30th September and 30.53% between 15th- 31st October (Figure 3).

Discussion

Zero tillage optimizes the sowing dates through retention of soil water (Buffer) from the long rains and advancement of sowing time through reduced time for land preparation by 20-30 days (Chandna *et al.*, 2004). Thus, it only requires a rainfall event or an irrigation event enough to trigger germination and the stored soil water will support crop growth until the next rain event. This is unlike in conventional tillage where the crop fully depends on received rainfall for germination, growth and development of the crop. This means that when the received rainfall results in seed germination and then a dry spell occurs for longer period than the crop can withstand water stress (moisture depletion to permanent wilting point), it eventually dies and this is regarded as a false start (Sen *et al.*, 2014). In this study, results of optimization analysis demonstrated that the probability of false start under conventional tillage was approximated 22.11% (Figure 3).

According to Tripathi *et al.,* (2013) research in India, a delay of every successive day in planting from the optimal sowing window decreased wheat grain yield progressively as was reported by Ali *et al.,* (2010). Consequently, farmers in India started practicing conservation technologies such as zero tillage to cut down on their production costs and avoid planting delays (Tripathi *et al.,* 2013).

Despite the high temperatures in ASAL areas, sowing date influences the yield of rain-fed crops like wheat due to erratic and unreliable rainfall especially at the onset of the rainy season. This is because rainfall directly influences soil water content which should be maintained at or near field capacity in conventional tillage. This is however not possible under conditions of erratic and unreliable rainfall. Based on the observed s differences in yields under conventional tillage, proper timing of the onset of the growing season has to be made.

In this study, a delay in sowing by ten days resulted to a loss of 6.7% while an early onset led to a loss of 37.1% under conventional tillage. This is attributed to the high evaporation and associated water stress. However, under zero tillage, an early onset resulted in a loss of 2.4% which is not significant ($p<0.05$), and a positive variation under delayed onset resulting in an increase of 12.4%.

These results demonstrate that under zero tillage, optimization of yields is possible through staggering of sowing dates within the sowing window. On the other hand, under conventional tillage in the study area, early onsets had high risks of crop failure or significant reduction in yield. Similarly, waiting for the wet season would complicate operations under this heavy clay soil and lead to soil degradation, (erosion, compaction and formation of hard surface hindering infiltration).

Conclusions and Recommendations

This study compared conventional and zero tillage practices against AquaCrop model generated sowing dates and wheat grain yields. In conventional tillage, timing and staggering of sowing dates had significant effect on grain yield, although with risks of high crop failure especially for the early onsets. Normal onset was the most appropriate sowing period. In zero tillage, crop yield was optimum in all sowing dates tested though early onset was better due to optimal soil moisture and early maturity of the crop.

Zero tillage can be embraced as a strategy to promote staggering of sowing dates without compromising grain yield or acreage under crop especially in ASAL areas. Finally, AquaCrop model is recommended as a useful tool for use with acceptable level of accuracy for scenario analysis in ASAL areas to optimize wheat crop yield production especially under rain-fed condition.

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