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Determination of Critical Period of Weed-Crop Competition in Rice (*Oryza sativa* L.) in Bench Maji and Kaffa Zone, South Western Ethiopia

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Abstract: Accurate assessment of crop weed interference period is an essential part for planning an effective weed management for cropping systems and, hence, can be considered the first step to design weed control strategy. The experiment was conducted at Guraferda and Gojeb, Southern Ethiopia during the 2016 main cropping season to assess the critical period of weed-crop competition and yield loss in rice. There were 14 treatments comprising: two series i.e. early (weedy up to 10, 20, 30, 40, 50, 60 and 70 days after crop emergence) and late (weed free up to 10, 20, 30, 40, 50, 60 and 70 days after crop emergence) competition periods were compared with two checks namely complete weed free and weedy check. The treatments were arranged in randomized complete block design with three replications for each set. The major weed species competing vigorously with rice were Cyperus assimilis, Setaria pumila, Phalaris paradoxa and Xanthium spinosum. With increasing duration of weed interference, weed dry weight, and the number of days of rice plant required to reach physiological maturity were increased whereas number of tillers per plant, panicle length, thousand seed weight, grain yield, aboveground biomass, and harvest index of the rice crop were reduced. Uncontrolled weed growth significantly reduced rice grain yield by 68% compared to the grain yield obtained from the weed-free check plots. The beginning and the end of critical period of weed crop competition were based on 5 and 10 % acceptable yield loss levels, which were determined by fitting logistic and Gompertz equations to relative yield data, representing increasing duration of weed-interference and weed-free periods. In conclusion, the results of the study revealed that, to reduce the loss in the grain yield of rice by more than 10% and higher economic return, it is important to keep the crop weed-free between 30 to 70 days after crop emergence at Guraferda, in Bench Maji Zone and 28 to 47 days after crop emergence at Gojeb in Keffa Zone.

Keywords: Critical Period, Gompertz Equation, Logistic Equation, Rice, Weeds, Yield Loss

1. Introduction

Rice is a staple food for more than half of the world's population. It is the most rapidly growing source of food in Africa, and is of significant importance to food security and food self-sufficiency in an increasing number of low-income food deficit countries. Therefore, improving the productivity of rice systems would contribute to hunger eradication, poverty alleviation, national food security and economic development [1]. In Ethiopia, rice is among the target commodities that have received due emphasis in promotion of agricultural production, and as such it is considered as the "millennium crop" expected to contribute to ensuring food security in the country. Although rice is introduced to the country recently, rice has proven to be a crop that can assure food security in Ethiopia, the second most populous nation in sub-Sahara Africa with about 99 million people in 2016 [2].

The principles of integrated weed management (IWM) should provide the foundation for developing optimum weed control systems and efficient use of herbicides [3]. The critical period for weed control (CPWC) is a key component of an IWM program. It is a period in the crop growth cycle during which weeds must be controlled to prevent yield losses [4-5]. Controlling weeds based on CPWC is the most appropriate way to optimize weed control applications [6]; [3]. With the aid of CPWC it is possible to make decisions on the need for and timing of weed control and to control weeds only when efficient weed control is required [7-8]. Studies on CPWC have been reported comprehensively in many crops in varying environments; but, studies on CPWC on rice are limited in Ethiopia in general and in Bench Maji and Keffa zone in particular. Therefore; the present study was initiated to determine the critical period of weed-crop competition and yield loss in rice crop.

2. Materials and Methods

2.1. Description of the Study Area

The experiments were conducted in Southern Nations Nationalities Peoples Region, Ethiopia during the 2016 main cropping *'Meher'* season, in Benchi Maji Zone at Guraferda site and in Kaffa zone at Gojeb site. The soil physico chemical analysis of the study areas revealed that the soils of the experimental field were clay and clay loam in texture both at Gojeb and Guraferda, respectively. The results also indicated that the soil of Gojeb and Guraferda are moderately and slightly acidic with pH of 6.31 and 5.66, respectively. The soils have medium organic carbon (1.46) and total N (0.09%) at Guraferda and low organic carbon (0.99) and total N (0.06%) at Gojeb. Available P is low both at Guraferda (6.30 ppm) and Gojeb (5.90 ppm).

2.2. Experimental Materials

The rice variety New Rice for Africa (NERICA- 4) was used for this experiment. NERICA rice varieties have been developed by Africa Rice scientists, and they are expanding and bringing the rice green revolution in different countries of Africa including Ethiopia. The new rice for Africa (NERICA) was developed by crossing *Oryza glaberrima* and *Oryza sativa*. The key features of the new varieties, panicle can hold up to 400 grains compared to the 75-100 grains of its African parents, with an increase in yield from 1 to 2.5 t/ha which can increase to 5 t/ha with fertilizer use. It also matures 30-50 days earlier than traditional varieties, contains 2% more protein than its parents and resist pests, tolerate drought and infertile soils better than Asian varieties. The adoption and cultivation of new rice varieties are increasing faster than any other food crops in many African countries [9].

2.3. Treatments and Experimental Design

The experimental treatments were arranged following the method described by [10]. Fourteen treatments in two series i.e. early (weedy up to 10, 20, 30, 40, 50, 60 and 70 days after crop emergence (IDWP) and late (weed free up to 10, 20, 30, 40, 50, 60 and 70 days after crop emergence (IDWFP) competition periods were compared with two checks namely complete weed free and weedy check. The design of the experiment was randomized complete block design with three replications. The experiment was conducted at two sites during 2016 main cropping seasons. The treatments were assigned to each plot randomly. The plot size was 3.00 m x 3.0 m. The frequency of weeding on the weed-free plots was based on the appearance of weeds. Growing degree days (GDD), which was used as an independent variable in regression analysis, was calculated as:

GDD=Σ (Daily average temperature-Base temperature).

The base temperature used in the calculation was 10°C.

2.4. Data Collection

2.4.1. Weeds Data

Weed flora: Data on weed flora present in the experimental fields were recorded during the experimental period. The weed species found within the sample quadrate were identified and classified into their respective groups.

Weed density: The weed density was recorded by throwing a quadrate (0.25 m×0.25 m) randomly at two places in each plot at the time of weed removal for early competition and about 15 days before the expected harvest time in the case of late competition to avoid possible foliage and seed shading. The weed species found within the sample quadrate were identified, counted and expressed in m^{-2}.

Weed aboveground dry biomass (g): For aboveground weed dry biomass, the weeds falling within the quadrate were cut near the soil surface immediately after recording data on weed count and placed into paper bags separately treatment-wise. The samples were sun-dried for 3-4 days and thereafter were placed into an oven at 65°C. temperatures till a constant weight and, subsequently, their dry weight was measured. The dry weight was expressed in g m^{-2}.

2.4.2. Crop Data

Number of days to 50% flowering: This parameter was recorded as number of days from emergence of rice to the first flower appeared on 50% of the plants in each plot.

Days to physiological maturity: It was recorded as the number of days from emergence to the day when 85% of the plants reached physiological maturity, *i.e.* both panicles and plants turned yellow (senescing) based on visual observation.

Plant height (cm): It was taken with a ruler from 10 randomly taken and pre tagged plants in each net plot area from the base to the apex of the main stem at physiological maturity.

Number of tillers per plant: Five plants were taken at random from each plot and total number of tillers per plant was recorded

Panicle Length per plant: Measurement was taken from basal node of the rachis to apex of each panicle. Each observation was average of 10 plants.

Thousand seed weight (g): 1000 seeds were counted and their weight was recorded at 10.5% moisture content for thousand seed weight.

Aboveground biomass (g): This parameter was determined by harvesting ten plants in each plot at physiological maturity and their dried aboveground biomass was recorded.

Treatment-wise per plant dry weight of straw was multiplied by the number of plants in respective treatments. This was considered as the aboveground dry biomass weight.

Grain yield (kg ha^{-1}): The grain yield was measured after threshing the sun-dried plants harvested from each net plot and the yield was adjusted at 10.5% seed moisture content. The grain weight obtained in ten plants was added to the final yield.

Harvest index (%): This parameter was calculated by dividing the grain yield by the aboveground biomass yield and multiplied by 100.

The maximum rice yield loss due to weed competition was calculated as:

$$= 1 - (\frac{\text{rice yield in weedy check}}{\text{rice yield in weed free check}}) \text{ x } 100) \quad (1)$$

2.5. Data Analysis

Data on weed density, weed dry biomass; crop phenology, growth, yield attributes and yield were subjected to analysis of variance (ANOVA) using GenStat 15.0 computer software [11]. Fisher's protected least significant difference (LSD) test at $p \leq 0.05$ was used to separate differences among treatment means [12]. As the F-test of the error variances for most parameters of the two sites was homogeneous, combined analysis of data was used.

To calculate the critical period of weed control in rice, the relative rice yield (*Y*) of each treatment was calculated as:

$$Y = (\frac{\text{rice yield in treatment}}{\text{rice yield in weed free check}}) \text{ x } 100) \quad (2)$$

and non-linear regression equations were used to fit the data using STATISTICA software [13].

The onset and end of critical period, which is the duration mandatory for controlling weeds was estimated by the response curve when both curves attained 90% of the relative yield gain and 10% of the yield loss of the complete weed-free period. The critical period was determined and found to be in between these two threshold points.

Analysis was based on the models suggested by [7]. The Gompertz equation was used for describing the effect of increasing duration of weed control on rice yield and the logistic equation was used for describing the effect of increasing duration of weedy period on rice yield. The Gompertz equation used was:

$$Y = a \exp[-b \exp(-k T)] \quad (3)$$

Where *Y* is relative yield, *a* is the yield asymptote, *b* and *k* are constants, and *T* is the time (x-axis expressed in GDD). The logistic equation used was:

$$= [(\frac{1}{\{\exp(c * (T - d)] + f\}}) + \left(\frac{(f - 1)}{f}\right)] \text{ x } 100 \quad (4)$$

Where *Y* is relative yield, *T* is the time (x-axis expressed in GDD); *d* is the point of inflection, *c* and *f* are constants.

2.6. Partial Budget Analysis

The concepts used in the partial budget analysis were the mean grain yield of each treatment in both locations, the field price of rice (sale price (ETB 15 kg^{-1}) minus the costs of harvesting, threshing and winnowing (ETB 165/100 kg) bagging (ETB 4.0 per 100 kg) and transportation (ETB 5 per 100 kg), the gross field benefit (GFB) per hectare (the product of field price and the mean yield for each treatment), the field price of hand weeding ETB 33 day^{-1}, the total costs that varied (TCV) included the sum of field cost of hand weeding and other costs for field management. The net benefit (NB) was calculated as the difference between the GFB and the TCV. All costs and benefits were calculated on hectare basis in Ethiopian Birr (ETB). Actual yield was adjusted downward by 10% to reflect the difference between the experimental yield and the yield farmers could expect from the same treatment. It was assumed that there was optimum plant population density, timely labor availability and better management (e.g. weed control, better security) under experimental conditions [14].

3. Result and Discussion

3.1. Weed Parameters

3.1.1. Weed Community

The major weeds in the experimental fields were broadleaved, grassy and sedges. Twenty three weed species found infesting the experimental fields belonged to eleven families. The major weed species competing vigorously with rice were *Cyperus assimilis, Setaria pumila, Phalaris paradoxa* and *Xanthium spinosum*. The weed flora present in the experimental fields is presented in table 1.

Table 1. *Weed community recorded in rice field at the experimental sites in 2016 cropping season.*

Weed species	Family	Life form (category)
Amaranthus hybridus L.	Amaranthaceae	Annual (Broad leaved weed)
Amharanthus spinosus L.	Amaranthaceae	Annual (Broad leaved weed)
Argemone Mexicana L	Papaveraceae	Annual (Broad leaved weed)
Commelina benghalensis L.	Commelinaceae	Annual (Broad leaved weed)
Commelina latifolia L.	Commelinaceae	Annual (Broad leaved weed)
Corchorus olitorius	Malvaceae	Annual (Broad leaved weed)
Cynodon nlemfuensis	Poaceae	Perennial (Grassy weed)
Cyperus assimilis Steud	Cyperaceae	Perennial (Sedge)
Cyperus esculantus L.	Cyperaceae	Annual (Sedge)
Cyperus rotundus L.	Cyperaceae	Perennial (Sedge)
Datura stramonium L.	Solanaceae	Annual (broadleaved)
Digitaria abyssinica	Poaceae	Perennial (Grassy weed)

Weed species	Family	Life form (category)
Eriocloa fatmensis	Poaceae	Perennial (Grassy weed)
Hygrophila auriculata	Acanthaceae	Annual (Broad leaved weed)
Launaea cornuta	Asteraceae	Perennial(Broad leaved weed)
Nicandra physalodes	Solanaceae	Annual (Broad leaved weed)
Oxygonum sinuatum	Polygonaceae	Annual (Broad leaved weed)
Parthenium hysterophorus L.	Asteraceae	Annual (Broad leaved weed)
Pennisetum clandestinum	Poaceae	Perennial (Grassy weed)
Phalaris paradoxa L.	Poaceae	Annual (Grassy weed)
Seteria verticillata (L.) Beauv.	Poaceae	Annual (Grassy weed)
Sonchus asper	Asteraceae	Annual (Broad leaved weed)
Xanthium spinosum	Asteraceae	Annual (Broad leaved weed)

3.1.2. Weed Dry Biomass

Significant differences were observed among the durations of weed competition on weed dry weight (Table 2). In general, weed dry weight increased with the increasing duration of the weedy period (IDWP) and decreased with the increasing duration of the weed-free period (IDWFP). In IDWP, the weeds might have exerted a severe competition and utilized the environmental resources for a longer period of time thus accumulating more dry matter. Whereas in IDWFP, the weeds emerged and grew after the respective weed-free periods under stress, thus, accumulating lower dry weight. The lowest weed dry weight (gm-2) was found at 70 DAE under IDWFP with the values of 9.9 and 61.9 gm-2 at 10 DAE under IDWP.

The highest weed dry weight was found in the weedy check at IDWP was in statistical parity with the values obtained 70 DAE (Table 2). At early crop growth stage, weeds may be better competitor than the crop, which is likely due to competitive advantages for the weeds in terms of preemption of resources. But with the advancement of times, crop start dominating over weeds, and after a certain stage, weed is no more a threat for crop growth, controlling weeds after that resulting no significant enhancement in crop growth. Similar findings have been reported by many researchers [15-17], who observed that weed interference up to a certain growth stage had negative impact on rice growth.

In IDWFP, the highest weed dry weight was found at 10 DAE with the values 152.6 and which was statistically in parity with 60 DAE (159.7 gm-2) under IDWP. The value at Guraferda was higher (162.6 gm-2) than the value obtained at Gojeb (81.6gm-2). The possible reasons for the higher weed dry weight at Guraferda than at Gojeb could be the relatively higher rainfall and temperature at the latter during the cropping season, which may have induced more accumulation of weed dry matter (Table 2). Moreover, the soil of Guraferda is more fertile than that of Gojeb, which may have favored weed growth. Corroborating the results of this study, [18] also reported that high amounts of rainfall and temperature influenced the periodicity of weed emergence, which often resulted in increased weed dry weight. The differences in weed composition and abundance between the two sites could be attributed to differences in weather, soil and previous management practices used [4]; [19].

Weed dry weight decreased significantly with the successive increases in the weed-free period. Similar result was reported by [20] who observed that weed density and dry weight decreased with increasing duration of weed-free period in an experiment conducted to determine the critical period of weed control in rice.

3.2. Crop Parameters

3.2.1. Days to Physiological Maturity

Significant differences were observed among the durations of weed competition in days to physiological maturity (Table 2). On the other hand, no significant differences existed in days to physiological maturity when weeds were allowed to grow up to 10 to 60 DAE. There was also no significant difference among weedy plots from 10 to 60 DAE. The weedy plots from 10 to 60 DAE were also in statistical parity among each other. Weedy plots up to 60 DAE were in statistical parity with the rest of the IDWP treatments except with 20 DAE treatments (Table 2).

Table 2. *Effect of increasing duration of weedy and weed-free periods on weed dry weight (g m-^{2}), days to 85% physiological maturity of rice at Gojeb and Guraferda in 2016 cropping season.*

Treatments	Weed dry weight (g m-2)	Days to 85% physiological maturity
Location		
Gojeb	81.6^{b}	108.8b
Guraferda	162.6^{a}	116.9^{a}
LSD(0.05)	19.4	0.4
DAE		
IDWP		
10	61.9^{fg}	114.1^{ab}
20	84.7^{def}	112.1^{cd}
30	91.8^{def}	113.8^{ab}
40	118.0^{cde}	113.5^{ab}
50	183.9^{b}	113.8^{ab}
60	159.7^{bc}	113.1^{bc}
70	281.7^{a}	114.6^{i}
WC	327.5^{a}	114.6^{a}
IDWFP		
10	152.6^{bc}	113.8^{ab}
20	109.3^{cdef}	113.83^{ab}
30	130.4^{bcd}	113.5^{ab}
40	87.9^{def}	111.3^{de}
50	72.7^{ef}	111.3^{de}
60	81.7^{def}	111.1^{de}
70	9.9^{gh}	110.8^{a}
WFC	0.0^{h}	110.5^{e}
LSD(0.05)	55.04	1.2
CV(%)	37.77	0.9

DAE = days after crop emergence; IDWP = Increasing duration of weedy period; WC = Weedy check; IDWFP = Increasing duration of weed-free period; WFC = Weed-free check; Means followed by the same letters within each column are not significantly different

The rice variety took the maximum days (116.9) to attain physiological maturity at Guraferda. The days required to reach physiological maturity of rice at Guraferda were relatively longer than those required at Gojeb. The probable reason could be relatively high rainfall and temperature observed at Gojeb which might have favored the growth and development of rice enhancing the days to reach physiological maturity.

In general, with increasing IDWP and decreasing IDWFP, the days required to reach physiological maturity increased. This means that the days required to attain physiological maturity increased as the duration of weed interference was prolonged (Table 2). The shading of crop plants by the weed canopy might have reduced sun light radiation thus prolonging the vegetative growth resulting in delayed days to physiological maturity. This in turn might have reduced vegetative growth and delayed the transition to the reproductive period and physiological maturity of rice. Similarly, [21] reported that with increase in the dry weight of weeds, the days required by the cowpea plants to reach physiological maturity were delayed.

3.2.2. Number of Tiller Per Plant

In IDWP treatments, no significant differences were found between 20 to 60 DAE. The IDWP treatments at 70 DAE had the lowest number of tillers per plant (9.3), which was in statistical parity with the number of tillers per plant at weedy check and 50 DAE. On the other hand, there were no significant differences between IDWFP treatments 10 to 40 DAE. Furthermore, keeping the plots weed-free from 50 DAE to 70 DAE resulted in a number of tillers per plant that was statistical parity with the number of tillers per plant from weed free check (14.6) (Table 3). Significant differences were observed in the number of tillers per plant due to locations. Rice plants at Guraferda had more number of tillers per plant than at Gojeb which might be the positive influence of relatively high amount of rainfall, temperature and fertile soil at Guraferda.

In general, in most of the treatments, number of tillers per plant was increased as weed interference decreased and the vice versa. This could be due to increased weed dry weight as weedy period increased and vice versa (Table 3). In line with this result, [22] reported that number of tillers per plants significantly increased with increasing length of weed-free period and decreased with increasing length of weed infested period in common bean. In contrast to this result, [23] reported that duration of weed interference did not significantly affect number of tillers per plant of irrigated common bean which could be due to more supply of water that might have increased the competitive ability of the crop.

3.2.3. Panicle Length Per Plant

Significant differences were observed in panicle length per plant at Gojeb and Guraferda. In IDWP treatments, the highest panicle length per plant (24.0) was obtained when the crop was kept weedy up to 40 DAE which was statistically at par with weedy from 10 DAE to 30 DAE. It was also revealed that keeping the plots weedy decreased the panicle length per plant (Table 3). In agreement with this result, [23] reported that panicle length per plant increased as weed interference period decreased and weed-free period increased.

3.2.4. Thousand Seed Weight

Increasing duration of weed-free period treatments had significant effect on thousand seed weight among the treatments (Table 3). In IDWFP, WFC had the highest thousand seed weight (42.8g). However, it did not differ significantly with weed-free up to 70 DAE. Thousand seed weight decreased with the increase in the duration of weedy periods and with the decrease in the duration of weed-free periods. Significant differences were observed in the thousand seed weight due to locations. Similar to the current result, [20] also reported that thousand seed weight were increased with the increasing length of weed-free conditions and decreased with the increasing length of weedy conditions.

Table 3. *Effect of increasing duration of weedy and weed-free periods on number of tiller per plant, number of panicle per plant, thousand seed weight (g)of rice at Gojeb and Guraferda in 2016 cropping season.*

Treatments	Number of tiller per plant	Panicle length per plant	Thousand seed weight (g)
Location			
Gojeb	11.1^{b}	23.2^{a}	38.1^{a}
Guraferda	11.9^{a}	14.4^{b}	37.1^{b}
LSD(0.05)	0.7	1.7	0.6
DAE			
IDWP			
10	12.8^{ab}	19.1^{cd}	37.2^{def}
20	11.4^{bc}	19.3^{bcd}	38.0^{def}
30	11.2^{bcd}	19.3^{bcd}	38.5^{cd}
40	11.4^{bc}	18.0^{cd}	37.4^{def}
50	10.3^{cde}	16.4^{d}	37.5^{def}
60	11.4^{bc}	21.0^{abcd}	37.5^{def}
70	8.5^{e}	8.8^{e}	31.4^{g}
WC	9.3^{de}	9.8^{e}	32.0^{g}
IDWFP			
10	10.6^{cd}	17.6^{d}	36.5^{ef}
20	10.6^{cde}	17.4^{d}	36.3^{f}
30	10.5^{bc}	19.4^{bcd}	38.2^{cde}
40	11.4^{bc}	20.8^{abcd}	38.5^{cd}
50	12.9^{ab}	22.8^{abc}	38.7^{cd}
60	13.2^{ab}	22.7^{abc}	40.0^{cd}
70	14.5^{a}	24.0^{ab}	41.4^{ab}
WFC	14.6^{a}	24.7^{a}	42.8^{a}
LSD(0.05)	2.0	4.8	1.7
CV (%)	15.4	22.1	4.0

DAE = days after crop emergence; IDWP = Increasing duration of weedy period; WC = Weedy check; IDWFP = Increasing duration of weed-free period; WFC = Weed-free check; Means followed by the same letters within each column are not significantly different

3.2.5. Grain Yield

There were no significant differences in the grain yield with weed free check (WFC) when the weedy period extended to 70 DAE, under increasing duration of weedy period treatments. A similar trend was observed between the weedy periods from 10 to 30 DAE while beyond this period the yield declined significantly. The yield obtained in weed-free check plot was in statistical parity with the yield obtained during the time spanning to 70 DAE, under increasing duration of weed free period. The weedy check plots also produced the lowest grain yield (2014.8kgha^{-1}), but the yield did not differ significantly with the yield obtained from the plots that remained weedy to 70 DAE. The decrease in yield with the increase in the duration of competition might be the result of increased weed dry weight, which might have influenced the number of tillers per plant.

Rice grain yield varied significantly with the variations in the duration of competition. Comparing the two sites, the highest rice yield was recorded at Gojeb whereas the lowest yield was obtained from Gurdaferda (Table 4). These might be due to differences in agro climatic conditions, soil moisture regimes, and weed flora among the experimental sites.

Rice grain yield decreased with prolonged delays in weed removal; conversely, grain yield increased with the increasing length of weed-free period. The rice yield losses in the weedy checks as compared to the weed-free checks were 68%. These values are very close to those reported in a previous study, where season long weed competition reduced yield by approximately 50% [24]. [16], recorded 79 and 66% yield reduction in rice due to weed competition till harvest in flooded and saturated conditions, respectively. [25], on the contrary, reported as high as 95% yield reduction in rice due to weed competition throughout the crop growing season.

3.2.6. Aboveground Dry Biomass Yield

The aboveground dry biomass yield of rice was significantly influenced both by the increasing and decreasing periods of weed competition. In IDWP treatments; no significant difference was found between 10 to 30 DAE. Similarly, no significant difference was observed between 40 to 60 DAE. The aboveground dry biomass yield of the weedy check plot, which was the lowest, was in statistical parity with the aboveground dry biomass yield obtained from plots which were kept weedy for 70 DAE (table 4). In line with the current finding [20] reported that adverse effect of increasing weedy period on biomass production increased gradually with the advancement of growth stages.

In IDWFP the lowest dry biomass (10128.1 kg ha-1) was recorded in plots which were kept weed-free up to 10 DAE. This value was in statistical parity with the plots which were weedy from 40 DAE to 60 DAE treatments. It was also observed that, the plots that were kept weed free from 40 to 70 DAE were not significantly different from WFC in the amount of aboveground dry biomass produced.

In general, at Gojeb, the aboveground dry biomass of rice was higher than Guraferda. The highest biomass yield (11619.1kg ha-1) was obtained from Gojeb site. Prolonged weed competition resulted in reduced biomass accumulation and lesser panicle length per plant and thousand seed weight which ultimately translated into lower grain yield. Increased biomass accumulation by weeds with the increasing span of weed interference period might also be a plausible cause of yield reduction in rice. As [16] stated, weed dry matter has been found to be highly correlated with crop yield loss.

3.2.7. Harvest Index

Harvest index was significantly affected by the duration of weed competition. In IDWP treatments, no significant difference was found between 10 to 40 DAE. Similarly, no significant difference was observed between 50 and 60 DAE. The mean harvest index of the weedy check plots, which was the lowest (24.0%), was in statistical parity with the harvest index obtained in plots kept weedy for 70 DAE. In IDWFP treatments, harvest index was significantly affected by the treatment. The rice harvest index at Guraferda exceeded the one at Gojeb but there were no significant different.

Table 4. *Effect of increasing duration of weedy and weed-free periods on grain yield, aboveground dry biomass yield, harvest index, yield loss of rice at Gojeb and Guraferda in 2016 cropping season.*

Treatments	Grain Yield	Aboveground Dry Biomass Yield	Harvest Index	Yield Loss
Location				
Gojeb	4582.47^{a}	11619.1^{a}	39.4^{a}	28.2^{b}
Guraferda	4049.98^{b}	10647.5^{b}	37.7^{a}	31.8^{a}
LSD(0.05)	177.83	416.1	1.7	3.06
DAE				
IDWP				
10	4622.0^{cde}	11574.8^{a-e}	39.9^{cd}	24.9^{efg}
20	4835.1^{bcd}	12432.8^{a}	39.0^{cd}	21.5^{fgh}
30	4804.0^{bcd}	12515.6^{a}	38.5^{de}	21.9^{fgh}
40	4189.0^{ef}	10699.2^{ef}	38.9^{d}	32.1^{de}
50	3513.2^{gh}	10910.0^{cdef}	31.8^{f}	43.0^{bc}
60	3317.8^{h}	10815.8^{def}	33.7^{ef}	46.2^{b}
70	2256.4^{i}	8503.2^{g}	26.5^{g}	63.9^{a}
WC	2014.8^{i}	8399.9^{g}	24.0^{g}	68.0^{a}
IDWFP				
10	3860.9^{fg}	10128.1^{f}	38.2^{de}	37.4^{cd}
20	4263.6^{ef}	11636.8^{a-e}	38.9^{d}	31.5^{de}
30	4494.5^{de}	11160.7^{b-e}	40.4^{cd}	27.9^{ef}
40	4672.8^{cde}	11944.6^{abcd}	39.3^{cd}	24.05^{efg}
50	5112.6^{bc}	11638.5^{a-e}	43.9^{bc}	16.8^{gh}
60	5272.7^{b}	11534.5^{a-e}	45.6^{b}	14.4^{h}
70	5800.6^{a}	12181.3^{ab}	47.6^{ab}	5.6^{i}
WFC	6079.5^{a}	12057.3^{abc}	50.8^{a}	1.0^{i}
LSD(0.05)	502.99	1177	4.9	8.67
CV (%)	10.10	9.1	11.12	25.02

DAE = days after crop emergence; IDWP = Increasing duration of weedy period; WC = Weedy check; IDWFP = Increasing duration of weed-free period; WFC = Weed-free check; Means followed by the same letters within each column are not significantly different

3.3. Critical Periods of Weed Control

Critical period of weed control (CPWC) was determined by using relative rice yield (% of season long weed-free yield) and growing degree days (GDDs) as quantitative variables in the regression analysis. Rice emergence date was used as the reference point for accumulation of GDD for accounting the possibility of weeds emerging before the rice. The CPWC was determined based on arbitrarily chosen yield loss levels (AYL) of 5% and 10%, which are judged to be acceptable considering the present economics of weed control.

The Gompertz and logistic equations generally described the data well as indicated by high coefficients of determination (R^2) values (Table 5). In Guraferda, the beginning of CPWC based on 10% AYL occurred by 595 GDD corresponding to 30 days after emergence (DAE) (Table 6). In contrast, in Gojeb at the same AYL, weeds required to be removed at 559 GDD, corresponding to 28 DAE. The end of the CPWC at 10% AYL occurred by 977 GDD or 47 DAE in the Guraferda and 984 GDD or 50 DAE in the Gojeb. At 5% AYL, the onset of CPWC occurred at 274 GDD, relating to 14 DAE in Guraferda and 276 GDD or 14 DAE in Gojeb. Weeds had to be controlled until 1128 GDD, corresponding to 56 DAE in Guraferda at 5% AYL. In contrast for the Gojeb and the same AYL, rice field should be kept weed-free until 1181 GDD, relating to 60 DAE (Fig 1 and 2).

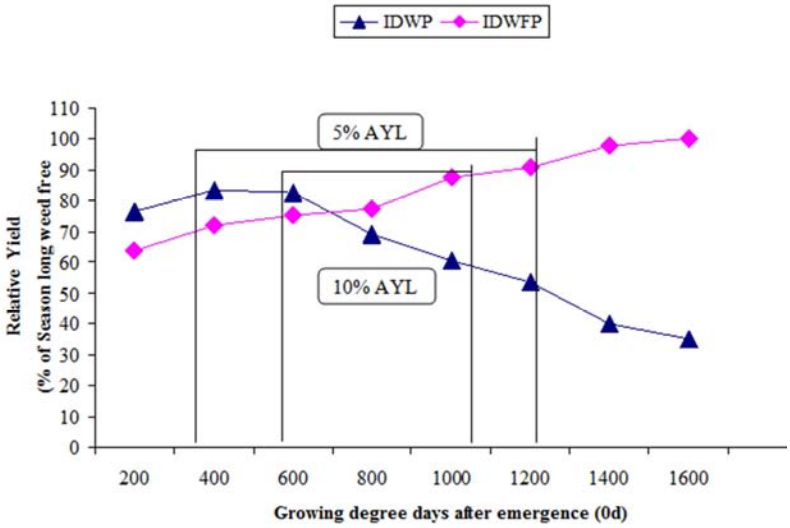

Figure 1. *Figure. Effect of weed crop competition on relative rice yield at Gojeb during 2016 main cropping season.*

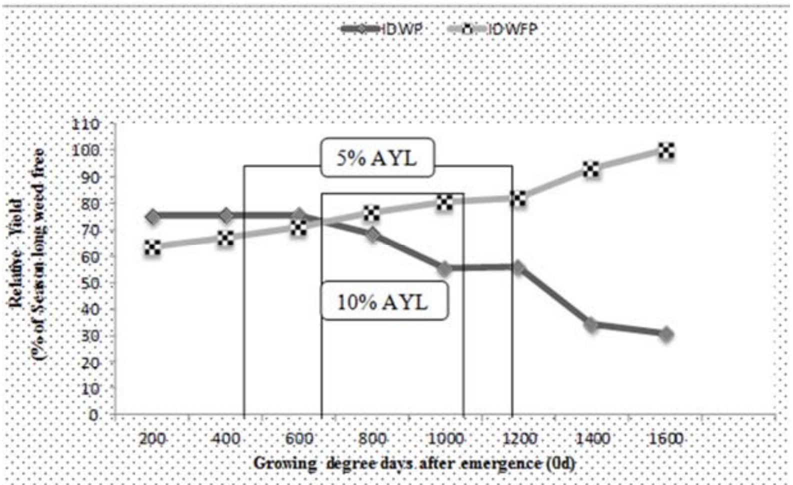

Figure 2. *Figure. Effect of weed crop competition on relative rice yield at Guraferda during 2016 main cropping season.*

Table 5. *Parameter estimates for the Gompertz and logistic equations for relative yield.*

Site	**Gompertz parameters**				**Logistic parameters**			
	A	**b**	**k**	**R^2**	**c**	**d**	**f**	**R^2**
Gojeb	100.2	1.29	0.895	0.97	0.25	0.565	1.17	0.99
Guraferda	102.1	1.37	0.089	0.95	0.27	0.018	1.52	0.97

Table 6. *The critical period of weed control (CPWC) calculated from Logistic and Gompertz equations at Guraferda and Gojeb locations during 2016 main cropping seasons.*

Yield loss levels (%)	**Guraferda**				**Gojeb**			
	Onset		**End**		**Onset**		**End**	
	GDD	**DAE**	**GDD**	**DAE**	**GDD**	**DAE**	**GDD**	**DAE**
5 %	274	14	1128	56	276	14	1181	60
10 %	595	30	977	47	559	28	984	50

It is evident from our study that CPWC of NERICA 4 was variable in length between locations and was a bit longer in Gojeb than in Guraferda. A long critical period is the indication of less competitive crop or more competitive weeds and vice versa [26]; [20]. A possible reason for starting earlier and lasting longer of CPWC in Gojeb might be the conditions favorable for weed germination and growth. Gojeb received more rainfall than Guraferda which might provide weeds an advantage over the rice crop. [16]; [20] also estimated longer CPWC of rice in longer season both flooded and saturated conditions. [27], on the contrary, observed differences in CPWC between seasons in irrigated lowland rice.

The beginning of the critical period was relatively stable between locations; the end, on the other hand, was more variable. The onset of CPWC became delayed and ended earlier as the predetermined AYL increased from 5% to 10%. This finding is supported by many researchers [7], [28], [8], [20], who indicated that the end of CPWC was variable and highly dependent on density, competitiveness, and emergence periodicity of the weed population.

3.4. Partial Budget Analysis

The result of the partial budget analysis and the data used for the partial budget analysis is given in Table 7. The partial budget analysis was done as described by [14] where the variable costs that vary included the cost of inputs (fertilizer) as well as the cost involved in their application.

However, for ease in calculation in place of field price of the crop, the cost incurred for harvesting, threshing, winnowing, packing and transportation was added to the variable input cost. The yield difference per hectare recorded by the different treatments account for the variation observed in value of gross benefit in both locations. The partial budget analysis indicated that the highest gross benefit was obtained from IDWF at 70 DAE (78308 ETB ha^{-1}) followed by 60DAE (71181 ETB ha^{-1}) while the lowest price was recorded from weedy check plots. In general, gross benefit increased with the increasing duration of the weed-free period (IDWFP) and decreased with the increasing duration of the weedy period (IDWP) except the treatments at 10 DAE. [29] reported a high economic return with butachlor + one hand weeding in rice also they observed that the use of butachlor took equivalent to186 hrs while two-hand weeding took 604 hrs ha^{-1} in rice.

Table 7. *Results of partial budget analysis of increasing duration of weedy and weed-free periods on in rice in 2016 main cropping season.*

	Average yield (kg ha^{-1})	Adjusted yield (kg ha^{-1}) 10% down	Total variable cost (ETB ha^{-1})	Gross Return (ETB ha^{-1})	Net return (ETB ha^{-1})
IDWP					
10	4622	4160	11925	62397	50472
20	4835.1	4352	11651	65274	53623
30	4804	4324	11010	64854	53844
40	4189	3770	9494	56552	47058
50	3513.2	3162	7886	47428	39542
60	3317.8	2986	6999	44790	37792
70	2256.4	2031	4813	30461	25649
WC	2014.8	1813	3856	27200	23344
IDWFP					
10	3860.9	3475	7219	52122	44903
20	4263.6	3837	8417	57559	49141
30	4494.5	4045	9358	60676	51318
40	4672.8	4206	10219	63083	52864
50	5112.6	4601	11473	69020	57547
60	5272.7	4745	12307	71181	58874
70	5800.6	5221	13693	78308	64615
WFC	6079.5	5472	14705	82073	67368

Cost of hand weeding and hoeing at 10 DAE 18 persons, WFC150 persons @Birr 33 $person^{-1}$, ETB= 0.0498 USD

4. Conclusion

Rice has great potential and can play a critical role in contributing to food and nutritional security, income generation, poverty alleviation and socio-economic growth of Ethiopia. The critical period for weed control (CPWC) is a key component of an IWM program. The results of this study indicated that the maximum rice yield losses due to the highest weed interference were 68%, as compared to the weed free check. To prevent more than 10% yield loss, the efficient weed control methods for rice variety NERICA 4 could be accomplished by keeping the crop weed free between 559 to 608 GDD (30 to 70 DAE) at Guraferda and 559 to 97 GDD (28 to 47) DAE at Gojeb. This could be done by using cultural, chemical, and integrated weed management practices. The partial budget analysis indicated that the highest gross benefit was obtained from IDWF at 70 DAE (78308 ETB ha^{-1}) followed by 60 DAE (71181 ETB ha^{-1}) while the lowest price was recorded from weedy check plots. In general, gross benefit increased with the increasing duration of the weed-free period (IDWFP) and decreased with the increasing duration of the weedy period (IDWP) except the treatments at 10 DAE.

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