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The critical period of weed interference in upland rice in northern Guinea savanna: Field measurement and model prediction

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Luxuriant weed growth destroying rice crops is a major problem in tropical Africa. The objective of this study was to determine the critical period of weed infestation in upland rice varieties in order to enable the development of more precise weed management recommendations for farmers. The effects of 10 differing periods of weed management on upland rice yield were studied in experiments with five rice varieties (three interspecific NERICA: NERICA1, NERICA2, and NERICA4) and the parents (*Oryza sativa* WAB 56-104 and *Oryza glaberrima* CG 14) during the 2004 and 2005 rainy seasons at Farako (Mali). INTERCOM model was used to explore the relationship between duration and timing of weed competition and rice crop yield loss, and the applicability of the model in rice cropping based weed management. The critical period of weed infestation determined from the field experiment was similar for the three New Rice for Africa (NERICA) varieties and the *O. sativa* parent (WAB 56-104), and was between 14 and 42 days after seeding (DAS). For the *O. glaberrima* parent (CG 14), the critical period was between 28 and 42 DAS. Weed competition either before or after these critical periods had negligible effects on crop yield. During the 2 years, yields of NERICA varieties and WAB 56-104 averaged 2700 and 400 kg ha^{-1} under weed-free plots and no weed control plots, respectively, indicating a yield loss of 85%. For GG 14, yields averaged 900 and 300 kg ha^{-1} under weed-free plots and no weed control plots, respectively, resulting in a 66% yield loss. The occurrence and composition of weeds during the two years were similar with a mean of 40% broadleaves, 35% grasses and 25% sedges. The most important weeds were *Imperata cylindrica*, *Cyperus sphacelatus* and *Digitaria longiflora*. During both calibration and testing efforts, the INTERCOM model satisfactorily simulated rice NERICA1 LAI, shoot dry weight and yields (r^2 ranging from 0.71 to 0.87). There appears to be room for improvement in the model with regard to the assumption that nutrients are not limiting to crop growth, but the use of the model for simulating the interactions between rice crop yield losses, weed density, and duration of weed competition appears promising. Results of this study can serve as a guide for optimum timing of weed control to maximize upland rice yield in West Africa.

Key words: Critical period, northern Guinea savanna, upland rice, New Rice for Africa (NERICA), INTERCOM.

INTRODUCTION

Weed control is one of the main upland rice yield limiting factors in West Africa. Therefore, weeds should be controlled and eliminated before competing with rice plants for light, water and nutrients. Intensive manual

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weeding is often practiced by farmers because the use of herbicides is associated with high costs and the failure of the distribution market, and the low rate of literacy among farmers in Sub-Saharan Africa (SSA) limits still more the use of herbicides (Rodenburg and Johnson, 2009). But manual weeding faces the following constraints: (i) manual weeding becomes acute with increased weed infestation if the field is cultivated for many years without a period of sufficient fallow, (ii) the weeding becomes difficult when the labor is insufficient mainly at the beginning of the rainy season when land preparation, planting and weeding all compete for the farmer's limited labor and (iii) manual weeding is done very often too late, when the weeds have outcompeted the crops leading to crop loss. In West Africa, is there a crucial period during which weed infestation is particularly harmful to upland rice? Thus for a sound integrated weed management in rice cropping, it is necessary to determine when rice plants will be the most and least harmed by weeds. The concept of critical periods of weed competition, during which weeds have the greatest effect on crop growth, was verified by Nieto et al. (1968). It is a specific minimum period of time during which the crop must be free of weeds in order to prevent loss in yield and represents the overlap of two separate components (Weaver and Tan, 1983). The first component is the length of time weeds can remain in a crop before interference begins. The second component is the length of time that weed emergence must be prevented so that subsequent weed growth does not reduce crop yield. The critical period is the prime period most suitable for conducting weeding operations taking into account the following factors: the environment (climate and soil), the period of weed infestation in the field, the weed species, the cultural practices including crop rotation, fertilization, density and methods of seeding (broadcast, hill seeding or transplanting), and the relative growth rates of the crop and its associated weeds. For example, according to Le Bourgeois and Marnotte (2002), the critical period is generally located between 15 and 60 days after seeding (DAS) for short-cycle annual crops (cotton, corn, sorghum, rice, etc.) and between 30 and 90 DAS for long-cycle crops (yams, cassava, sugarcane, etc.). In rainfed rice in southern Togo, weed competition is more harmful between 21 and 30 DAS (Boyoda, 1991). In the areas of northern Guinea savanna characterizing southern Mali, farmers generally weed their fields one or twice (extension services often recommend two weedings), but the weeding operations are often late. Inevitably in rainfed rice cultivation in these areas, the concept of critical period or critical threshold leads to severe competition between weeds and rice plants.

The use of the term critical threshold in integrated weed management to predict when weeds must be controlled to prevent yield loss was proposed by Dawson (1986). The economic threshold could be also calculated to indicate the length of time during which a crop could tolerate the competition of weeds before yield losses exceeded the costs of control (Weaver et al., 1992). This would lead to the early-season threshold that signals the beginning of the critical period, and the late-season threshold the end. Van Heemst (1985) has shown that the end of the critical period is related to the competitive ability of the crop. Thus, a crop with a high competitive ability has a critical period that ends early. Critical period of weed control has commonly been reported as day after seeding (DAS), but due to differences in planting dates and environment, this may generate different results among sites, seasons, and varieties (Anwar et al., 2012). Studies have also reported critical period as growing degree days because it is a biologically meaningful measure of time required for plant growth and development, and therefore, it would be applicable for comparing critical period across different agro-climatic conditions (Evans et al., 2003; Anwar et al., 2012). The critical period is usually determined through empirical mean comparison and multiple regression statistical tests. Cousens (1988, 1991) suggested using fitted responses curves to determine these critical thresholds. This allows a more accurate estimation of yield losses but still suffers from problems associated with empirical relationships. Because these parameters of response curves can vary depending on factors such as the crop and the associated weed species, the weed density, and especially the environmental conditions (Weaver et al., 1992). A dynamic simulation tool such as INTERCOM can be used to examine in detail the effect of these factors on the length of the critical period for upland rice crops. The model has been used for crop-weed competitions including crops such as corn (Lindquist and Mortensen, 1997; Cavero et al., 2000), leek and celery (Baumann, 2001), and rice (Kropff and van Laar, 1993; Akanvou, 2001). This model is basically a growth model of two or more species that are linked through additional routines that govern distribution of resources such as light and water over the competing species (Bouman et al., 1996; Akanvou, 2001). Precise technical guidelines to identify the critical period of weed competition of upland rice and mainly for one group of interspecific rice varieties known as NERICA developed by the Africa Rice Center (AfricaRice) and partners, are still scant (Wopereis et al., 2008).

The objectives of this study were to identify the weed flora, to assess the in-field critical period for weed competition with upland rice, and to evaluate the performance of the INTERCOM, a dynamic and process-based simulation model that can be used to realistically address the effects of the duration of weed competition on upland rice crop yields.

MATERIALS AND METHODS

Experimental site

The experiment was conducted from 2004 to 2005 under rain fed conditions in northern Guinea savanna agroecology in southern Mali at the agricultural research station of the IER (*Institut*

Table 1. Air temperature and rainfall data during cropping seasons (June-October) 2004-2005.

Month	2004			2005		
	T_{min} (°C)[a]	T_{max} (°C)	Rainfall (mm)	T_{min} (°C)	T_{max} (°C)	Rainfall (mm)
June	23.1	33.6	78.6	22.2	32.2	292.1
July	21.9	30.2	325.5	22.0	30.4	197.7
August	21.6	30.3	285.3	21.5	29.6	275.8
September	21.5	31.3	141.5	21.7	31.2	174.0
October	22.5	34.2	52.7	22.0	33.6	52.3

[a]T_{min} (°C), Minimum air temperature in degree Celsius; T_{max} (°C), Maximum air temperature in degree Celsius

d'Economie Rurale) of Farako (Sikasso) (11° 12' 48.9"N, 5° 27' 16.7"W, 400 m above sea level). The climate falls within the open woodland savanna agroecological zone with a monomodal rainfall pattern averaging annually 1130 mm. The rainfall pattern is characterized by one single pick, increasing in amount and frequency, reaching a maximum in July/August/September. The average daily temperature is 28°C with a range between 22 and 34°C. The air temperature and rainfall data during the cropping season (June to October) were collected during the experiment and are presented in Table 1.

According to the analytical procedures of the International Institute of Tropical Agriculture (1989), the average chemical analysis of topsoil 0 to 20 cm showed soil pH in water 1:1 = 5.8, organic carbon content of 0.46%, organic matter 0.79%, nitrogen 0.30‰. The textural class of the soil is sandy loam with sand, silt and clay content of 84, 11 and 5%, respectively. At field capacity on wet basis, soil water retention was 19% and wilting point was 9%, and the soil is classified as acidic Acrisol (FAO, 1998). The study area has been previously sown to sorghum (*Sorghum bicolor* L.) for 2 years, and left to a short fallow of 1 year of *Imperata cylindrica* (L.) Raeuschel and *Digitaria longiflora* (Retz.) before the experiment. These two weed species accounted for more than 80% of the weed population found on the site at the onset of the experiment.

Field experiment

Experimental design

A split-plot design was used, with ten weeding regimes on the plot level and five upland rice cultivars on the sub-plot level, in four replicates. Ten weeding regimes treatments (WD14–WFharv) were devised to examine the effects of differing periods of weed control and interference, and were similar to those of Nieto et al. (1968) and Johnson et al. (2004). The treatments were:

(1) WD14: Weedy until 14 DAS,
(2) WD28: Weedy until 28 DAS,
(3) WD42: Weedy until 42 DAS,
(4) WD56: Weedy until 56 DAS,
(5) WDharv: Weedy from seeding to maturity,
6) WF14: Weed-free until 14 DAS,
(7) WF28: Weed-free until 28 DAS,
(8) WF42: Weed-free until 42 DAS,
(9) WF56: Weed-free until 56 DAS,
(10) WFharv: Weed-free from seeding to maturity.

Weed growth was controlled in the required periods for each of the above treatments, and hand weeding was weekly undertaken as needed. The term "weed-free" in the treatments therefore indicates the period during which weeds were removed at weekly intervals.

The five varieties for the sub-plots were three NERICAS: NERICA1, NERICA2, and NERICA4, and the two parents: *O. sativa* L. WAB 56-104 and *O. glaberrima* Steud, GC 14. Sub-plot size was 4 by 3 m with rice hill distances of 0.2 by 0.25 m.

Soil and crop management

The land was disc-ploughed and harrowed once before the plots were laid out. Seeding dates were 26 June in 2004 and 23 June in 2005. Rice was dibble-seeded at a rate of five to six seeds per hill, and then seedlings were thinned to four plants per hill at 14 to18 DAS in order to have a population density of 800000 plants ha^{-1}. Fertilizer at a rate of 10N-18P_2O_5-18 K_2O kg ha^{-1} was uniformly broadcast on the tilled fields and incorporated into the soil prior to rice seeding. In addition, 33 kg N ha^{-1} (as urea) of fertilizer was broadcast at 21 and 42 DAS. These fertilizer rates are recommended by Africa Rice (Sahrawat et al., 2001). The plants were protected against nematodes and termites by applications of carbofuran at the rate of 2.5 kg ai ha^{-1} at seeding.

Data collection and statistical analysis

Weeds and rice were sampled from two 0.5 m^2 quadrats taken in each plot at 14, 28, 42, 56, and at harvest, with plants being cut at ground level. The weeds were separated from the rice into different species and all biomass was weighed. Two 500 g sub-samples of each species were oven-dried and weighed to allow correction of the fresh weight data. The numbers of days to maturity for rice varieties were recorded. At harvest, yield components were observed by taking samples from a 0.25 m^2 quadrat per plot. Yield components recorded were: the number of panicles, tiller number per square meter, percent of full grains, number of spikelets per panicle, and 1000-grain weight. Grain yield was recorded from 6 m^2 quadrats and corrected for 14% moisture content. The relative frequency of major weeds was determined as the percentage of plots in which the species were present.

Statistical analyses were performed using the mixed model with maximum likelihood (REML) for the estimation of the variance over the years (SAS Institute, 2004). Fixed effects were the year, weeding regimes and varieties, while replicates and their interactions with weeding regimes accounted for random effects. Mean separation was performed using the SAS LSMEANS test (pair-wise comparisons) at $P \leq 0.05$.

Simulating the effects of the duration of weed competition on crop yields

The model INTERCOM (Kropff and van Laar, 1993) was used to assess the relationship between duration and timing of weed competition and rice crop yield losses. Indeed, the influence of length of time that weeds were present in the crop and the associated crop yield was assessed in the context of the critical period of weed competition. The critical periods were determined by changing the dates of weed emergence (DOYEM parameter) and the dates of weed removal (KILDAY parameter) in the model in order to determine associated yield by simulating crop growth. Overall, the INTERCOM model was evaluated by first calibrating the model based on the sensitivity analysis using measured data of LAI and shoot dry weight and its performance was tested against measured yield data.

Model overview

The structure of the simulation model INTERCOM was described by Kropff and van Laar (1993). The model simulates growth of the crop and weeds from emergence through crop maturity as a function of solar radiation, temperature, water availability, and species characteristics on a daily time step basis. Interactions are simulated by distributing the growth-limiting resources of light and water over the competing species and assuming that neighboring species (rice crop and weeds) mutually reduce their growth only by modifying the environment and changing water and light availability. The amount of resources acquired by a species determines its growth rate. Nitrogen and other nutrients are assumed to be available in sufficient amount and the effects of insects and diseases on crop and weed growth are neglected (Kropff et al., 1992). Input data for the model are daily weather information (maximum and minimum temperatures, total global radiation, and rainfall), weed densities and dates of crop and weed emergence.

In a potential production system, where light, temperature and physiological and morphological characteristics determine the growth of a plant community, plants only compete for the resource light. In agricultural systems where other factors like nitrogen or water limit crop production weeds compete with the crop for light as well as for the other resources (Kropff and van Laar, 1993). Key complex interrelationship processes are described in the INTERCOM model (Kropff and van Laar, 1993) as follows:

Light interception by the canopy: The photosynthetically active radiation (PAR) supplies the plants with energy for CO_2 assimilation. The assimilated CO_2 is converted into carbohydrates (CH_2O). The overall simplified chemical reaction of the process is:

$$CO_2 + H_2O \xrightarrow{\text{Light}} CH_2O + O_2 \qquad (1)$$

The incoming radiation is partly reflected by the canopy. The reflection coefficient (ρ) of a green leaf canopy with a random spherical leaf angle distribution, which indicates the fraction of the downward radiation flux that is reflected by the whole canopy can be approximated by the following equation (Goudriaan, 1986):

$$\rho = [(1 - \sqrt{(1-\sigma)}) / (1 + \sqrt{(1-\sigma)})] \bullet [2 / (1 + 1.6 \sin \beta)] \qquad (2)$$

in which σ represents the scattering coefficient of single leaves for visible radiation and the sinβ is the sinus of the solar elevation (β).

Then the radiation fluxes decrease within the canopy with the cumulative leaf area index (*LAI*), counted from the top downwards (Kropff and van Laar, 1993):

$$I_L = (1 - \rho)\ I_0 \exp(-k \times LAI) \qquad (3)$$

Where, I_L is the net PAR flux at depth L in the canopy (MJ m^{-2}ground s^{-1}), I_0 is the flux of visible radiation at the top of the canopy (MJ m^{-2}ground s^{-1}), *LAI* is the cumulative leaf area index from top downwards of the canopy (m^2 leaf m^{-2} ground), ρ is the reflection coefficient of the canopy (-), and k is the extinction coefficient for PAR (-).

The light absorbed by species (I_{abs}, MJ m^{-2} s^{-1}) is obtained by taking the first derivative of Equation 3 with respect to LAI:

$$I_{abs} = -dI_L/dL = k\ (1 - \rho)\ I_0 \exp(-k \times LAI) \qquad (4)$$

Biomass production: Gross canopy photosynthesis of the species is calculated based on the photosynthesis light-response of individual leaves which is characterized by the initial light use efficiency of leaf CO_2 assimilation ($\mathcal{E}$, kg CO_2 ha^{-1} leaf h^{-1}/J m^{-2} leaf s^{-1}) and the light saturated of CO_2 assimilation (Amax, kg CO_2 ha^{-1} h^{-1}, Spitters et al., 1989; Akanvou, 2001).

Leaf area: The expansion of leaf area determines the amount of intercepted light by the canopy, and is simulated as an exponential function of accumulated degree-days (Kropff and van Laar, 1993):

$$LAI\ (tsum) = LA0 \times N \times \exp(RGRL \times tsum) \qquad (5)$$

Where, *LA0* is the leaf area index at seedling emergence (m^2 leaf $plant^{-1}$); t*sum*, the accumulated degree-days since emergence (°Cd); *RGRL*, the relative leaf area growth rate $(°Cd)^{-1}$; and *N* the number of plants (m^{-2}).

Model calibration

Sogbedji et al. (2001) defined the calibration as being the process of adjustment of the model parameters within an expected range of published values to minimize the difference between observed and simulated data. Based on sensitivity analyses (Kropff et al., 1994), we calibrated the model by performing multiple runs and sequentially adjusting the following input parameter: (1) the maximum assimilation rate of individual leaves, *AMAX*, (2) the specific leaf area, *SLA* and (3) the leaf area index at seedling emergence, *LA0* to optimize the fit between simulated and measured data of shoot dry matter and leaf area index. All model parameters input parameter values (Table 2), except those adjusted in the calibration procedure, were selected from Kropff et al. (1994) and Akanvou (2001). Simulations covered the crop growth period of the two years (2004 and 2005) during which shoot dry matter and leaf area index data were collected at specific dates including emergence and 14, 28 and 56 DAS. The calibration consisted of slight increases or decreases of each parameter within a range of published values (Table 2) during each run, and was completed when adjustments to the specific parameter no longer reduced the difference between measured mean and simulated values of shoot dry matter and leaf area index. We followed the methods of Addiscott and Whitmore (1987), using a positive, highly significant correlation coefficient, and a reduced mean difference between simulated and measured data as criteria for goodness of fit of model predictions. To assess the accuracy of simulations, we used graphical and statistical methods (Loague and Green, 1991; Willmott, 1981). Simulated values were plotted against the corresponding measured values on a 1:1 scale to examine trends. We assumed a linear relationship between measured and simulated data, and used PROC REG of the SAS software package (SAS Institute, 2004) to conduct least squares regression analysis. The root mean square error (RMSE) was compared to the mean measured value (normalized root mean square error, NRMSE) to determine the prediction error. The statistical methods also included calculation of Willmott's index of agreement (*d*). The value of *d* reflects the degree to which the simulated variation accurately estimates the measured variation, and its value is 1.0 when there is a perfect agreement between simulated and measured values.

Table 2. INTERCOM parameter input values used in the simulations for NERICA1. Functions in the table are related to thermal time (°Cd).

Function description	Abbreviations	Units	Values
Development rate during vegetative phase	DVRV	$(°Cd)^{-1}$	0.000845
Development rate during reproductive phase	DVRR	$(°Cd)^{-1}$	0.00152
Light extinction coefficient for leaves	KDF		0.6
Photosynthetic rate	AMAX	kg CO_2 ha^{-1}leaf h^{-1}	0,51;1000,40; 1200,27; 2200,5
Dry matter distribution pattern above ground (leaves-stems-panicles)	RGRL	$(°Cd)^{-1}$	0.0075
Initial leaf area	LA0	m^2 $plant^{-1}$	0.0000682
Relative death rate of the leaves	RDRLV		1162,0 ; 1222,0.0071; 614,0.0028; 2200,0.029
Specific leaf area	SLA	m^2 kg^{-1}	0,20.4; 141,21.4; 15,24; 418,25.2; 656,17.6 ; 912,15; 230,22; 2200,23

Mean difference, RMSE, NRMSE, and *d* are defined as follows:

Mean Difference (MD) $= \sum (O_i - S_i)/n$

$$\text{RMSE} = \left[\sum_{i=1}^{n} (oi - si)^2 / n \right]^{0.5}$$

NRMSE = RMSE /*o*

$$d = 1 - \frac{\sum_{i=1}^{n} (o_i - s_i)^2}{\sum_{i=1}^{n} (|o'_i| + |s'_i|)^2}$$

Where $O'_i = O_i - o$ and $S'_i = S_i - o$. *n* is the number of observations, O_i is the value observed, and S_i is the corresponding simulated value, and *o* is the mean observed value.

Data collection for model simulations

In the two field experiments conducted in 2004 and 2005 as described above, focus was placed on the variety of rice NERICA1 and the calibration task was performed using data from field plots without weed infestation. Measurements started one week after rice emergence and during both years samplings were taken every two weeks. At each sampling date, the height of the plants was recorded. Destructive samplings were performed on a quadrat of 0.5 m^2. The above ground parts of plants were separated from the roots. The samples were further partitioned between the leaves, stems and the storage organs, and dried in the oven at 70°C for 72 h and the leaf area index was measured on a subsample of leaves using the LiCor LI-3000 (Lincoln, Nebraska). Phenological and physiological data used for model parameterization for the rice variety NERICA1 and the weed species were derived from literature (Akanvou, 2001) and from the first experiment in 2004. Data on densities of rice plants and weeds, and the dates of emergence (50%) of rice plants and weeds were collected on the experiments conducted in 2004 and 2005. Weather data was collected at the Sikasso airport located at around 20 km from the study area. Yield data were collected from the ten weed regimes (weed-free and weed-infested regimes) as described above and were used for model performance testing.

Model testing

The performance of the calibrated model was tested, using the yield data from both experimental plots with and without weed infestation. The calibrated model was executed for the 2004 and 2005 years without any changes to the values of the calibrated parameters (AMAX, SLA, and LA0) and simulated and observed yield data were compared. The graphical and statistical methods described in the calibration section were used for the comparisons.

RESULTS AND DISCUSSION

The relative frequencies of major weeds

During the 2 years of experimentation, 22 main weed species were identified in 2004, and 26 in 2005 (Table 3). There was the same number of species for broadleaf weeds and grasses, and sedges represented the lowest number. The vegetation was almost homogeneous with the grasses and sedges represented by *Imperata cylindrica* (grass) (66%), *Cyperus sphacelatus* (sedge) (51%) and *Digitaria longiflora* (grass) (37%) that were the dominant weed species. By grouping weeds according to their methods of reproduction and dispersal determining their life cycle, the following groups were distinguished (annual grasses, broadleaved species and sedges, and perennial grasses, broadleaved species and sedges) (Table 3). Thus, the annual weeds that complete their life cycle within one year or less were the most common group during the two \\years of study. The group of perennial weeds was the second group in terms of fre-

Table 3. Relative incidence (%) of main weeds at harvest, Farako, (2004-2005).

Species	2004	2005
Annual sedges species		
Cyperus sphacelatus	45	56
Mariscus squarrosus	9	3
Perennial sedges species		
Cyperus rotundus	6	9
Cyperus spp.	25	36
Cyperus tenuiculmis	15	23
Annual grasses species		
Dactyloctenium aegyptium	24	11
Digitaria horizontalis	5	15
Digitaria longiflora	35	38
Digitaria spp.	10	24
Eleusine indica	6	5
Paspalum scrobiculatum	1	3
Pennisetum spp.	-	3
Pennisetum polystachion	1	-
Rottboellia cochinchinensis	1	3
Setaria pumila	-	4
Perennial grasses species		
Imperata cylindrica	63	68
Annual broadleaved species		
Acanthospermum hispidum	18	21
Aeschynomene americana	-	6
Ageratum conyzoides	3	1
Borreria stachydea	1	-
Borreria verticillata	-	4
Indigofera hirsuta	5	-
Mitracarpus scaber	-	1
Oldenlandia herbacea	-	1
Spilanthes filicaulis	3	1
Tephrosia argentea	-	1
Vernonia pauciflora	15	23
Perennial broadleaved species		
Scoparia dulcis	6	1
Smilax krausiana	8	3

quency. Broadleaved weeds were numerous but they had lower frequency than grasses and sedges, and have also experienced the most significant interannual floristic changes (Table 3).

Effects of critical periods on grain yields

Rice grain yields from the different periods of weed competition during the raining seasons of 2004 and 2005 are shown in Table 4. Rice grain yields were calculated in relation to the control plot (weed-free) to harvest (WFharv). Average yields (kg ha^{-1}) for the two years (2004-2005) of each variety in weed-free plots were: NERICA1: 1735; NERICA2: 1706; NERICA4: 2698; WAB 56-104: 1648; GC 14: 965. In the unweeded plots throughout the cropping cycle of varieties, yields (kg ha^{-1}) were: NERICA1: 450; NERICA2: 410; NERICA4: 728; WAB 56-104: 459; GC 14: 252. The average relative yields of the unweeded plots compared to the weed-free

Table 4. Effects of the period of interference of weeds on the yield of rice, Farako, 2004 and 2005.

Weeding regimes	Variety	2004 rice yield (kg ha^{-1})	Rice grain yield (%) compared to weed-free	2005 rice yield (kg ha^{-1})	Rice grain yield (%) compared to weed-free
Early competition	NERICA1				
WD14		1771[a]	98	1599[a]	96
WD28		1601	88	1453	88
WD42		1520	84	1380	83
WD56		1123	62	842	51
WDharv (unweeded)		502	27	398	24
Late competition					
WF14		483	27	626	38
WF28		1376	76	985	59
WF42		1720[a]	95	1562[a]	94
WF56		1756[a]	97	1625[a]	98
WFharv (weed-free)		1811[a]	100	1658[a]	100
LSD ($P < 0.05$)		192		155	
Early competition	NERICA2				
WD14		1632[a]	92	1718[a]	105
WD28		1501	85	1503[a]	92
WD42		1452	82	1224	75
WD56		532	30	568	35
WDharv (unweeded)		434	25	386	24
Late competition					
WF14		917	52	863	53
WF28		1235	70	1110	68
WF42		1716[a]	97	1586[a]	97
WF56		1683[a]	95	1510[a]	92
WFharv (weed-free)		1771[a]	100	1642[a]	100
LSD ($P < 0.05$)		220		140	
Early competition	NERICA4				
WD14		2881[a]	94	2315[a]	99
WD28		2388	78	2176[ab]	93
WD42		2092	68	1910	82
WD56		1731	57	1546	66
WDharv (unweeded)		803	26	653	28
Late competition					
WF14		991	32	785	34
WF28		1894	62	1689	72
WF42		2907[a]	95	2010[ab]	86
WF56		2968[a]	97	2290[a]	98
WFharv (weed-free)		3059[a]	100	2337[a]	100
LSD ($P < 0.05$)		468		365	
Early competition	WAB 56-104				
WD14		1588[a]	96	1514	93
WD28		1326	80	1289	79
WD42		1237	75	1165	71
WD56		840	51	687	42
WDharv (unweeded)		485	29	431	26
Late competition					
WF14		839	51	769	47

Table 4. Contd.

WF28		1254	76	1032	63
WF42		1577[a]	95	1485[a]	91
WF56		1611[a]	97	1602[a]	98
WFharv (weed-free)		1660[a]	100	1636[a]	100
LSD (P < 0.05)		242		154	
Early competition	CG 14				
WD14		983[a]	105	936[a]	94
WD28		997[a]	106	897[a]	90
WD42		706	75	676	68
WD56		682	73	666	67
WDharv (unweeded)		275	29	229	23
Late competition					
WF14		685	73	280	28
WF28		740	79	642	65
WF42		890[ab]	95	920[a]	93
WF56		909[ab]	97	972[a]	98
WFharv (weed-free)		937[a]	100	992[a]	100
LSD (P < 0.05)		192		228	

The averages in a column followed by the same lowercase letter are not significantly different from the control plot weed-free until the harvest at P < 0.05.

(reflecting relative yield losses) for the five upland rice varieties were 74, 76, 73, 72, and 74%, respectively for NERICA1, NERICA2, NERICA4, WAB 56-104 and CG 14, with an average of 74%. This figure lies in the range of yield loss due to uncontrolled weed growth in upland rice ecosystems in West Africa (Akobundu, 1980; Dzomeku et al., 2007). For the two scenarios in Mali (weed free and unweeded plots to harvest), NERICA4 variety had significantly higher yield (P<0.05) than the other varieties, implying a better weed competitiveness of this variety in this northern Guinea savanna environment. This character of NERICA4 may have played a predominant part in its dissemination and adoption in the southern Mali agroecology (AfricaRice, 2008). In the present study, NERICA4, with a height of 120 cm, was the tallest variety among the NERICAS tested, and the advantage of height was seen as a morphological advantage for competition with weeds (De Vida et al., 2006; Zhao et al., 2006; Moukoumbi et al., 2011).

Increasing periods of weed interference in the early stages of the rice plants (WD14-WDharv) caused a steady decrease in rice yields for the five varieties. For the 2 years combined, daily yield losses of 17, 27, 23 and 18 kg ha^{-1} of rice grain were found respectively for varieties NERICA1, NERICA2, NERICA4, and WAB 56-104, when weeding was delayed between 14 and 56 DAS. For CG 14, yields loss was less significant and was around 6 kg ha^{-1}. In the early competition group, mean rice yields for the three NERICAS and WAB 56-104 were equal to that of the weed-free control when the first weeding was performed at 14 DAS (Table 4). There were significant yield differences relative to the weed-free control when this first weeding was done at 28 DAS or later. For the late competition group treatments, the results did not differ significantly from the weed-free control when weeding was stopped 42 DAS or later. Under the experimental conditions, only plots in which weeding was stopped at 14 and 28 DAS gave significantly lower yields than the weed-free control. The early weed competition threshold occurred at 14-28 DAS, and the late weed competition threshold was between 28-42 DAS. Thus concerning the NERICAS and their sativa parent WAB 56-104, the critical period for weed competition was estimated as the time interval between these two thresholds, that is, 14-42 DAS. For *O. glaberrima* CG 14, the critical period was between 28-42 DAS (Table 4). For CG 14, the yield loss between the start and the end of the critical period was less important, indicating the ability of this variety to better withstand weeds during this period, and also suggesting that the first weeding for this variety may be delayed up to 28 DAS. Thus the critical period for this variety would then extend from 28 to 42 DAS or 14 days instead of 28 days for the other varieties.

First weeding of CG 14 may be delayed up to 28 DAS without significant yield loss because during its vegetative phase, this variety produces more vigorous seedlings and many tillers to better compete with weeds (Koffi, 1980). Although CG 14 could be competitive with weeds, it had low yield potentials (Table 4). And for CG 14 and other *O. glaberrima* varieties, yield losses are mainly due to their lodging and grain shattering characteristics (Koffi, 1980).Figure 1 highlights the negative effect of the early competition with the most important rice yield loss

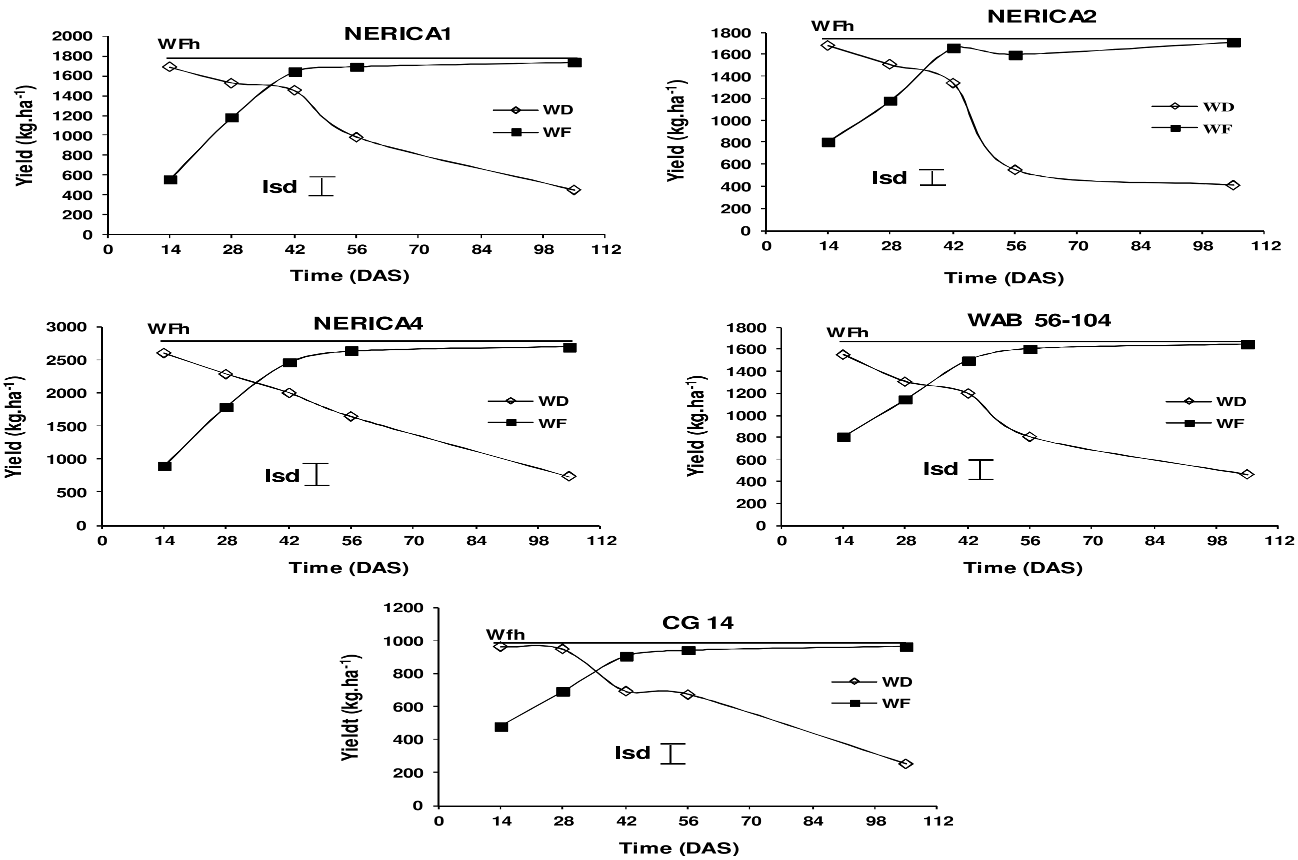

Figure 1. Rice yields in plots subjected to early competition (WD) and those subjected to late competition (WF). WFh: weed-free plots to the harvest. Farako (2004-2005).

due to early competition, and a lesser loss due to late competition. Then in Figure 1, there is a point of intersection (approximately 35 DAS) between the time during which weeds may remain in the plots and the period of time during which the plots should be weeded, suggesting that a single weeding at this time can prevent significant yield loss. But the present study did not include the effect of weeding on this specific date of 35 DAS. Nevertheless a previous study (Touré et al., 2011) were able to establish that a single weeding done at 31 DAS (close to 35 DAS) had a yield comparable to the double weeding done at 21 and 42 DAS. If a single weeding done on a specific date between 31 DAS and 35 DAS did not have a significantly lower yield than the wee-free control, then it would not be a critical period, but a critical date for weeding. Therefore, the critical period for the different rice varieties was from 14 to 42 DAS or 28 days, and during this period weeds should be theoretically removed. This critical period of weed control is in compliance with previous studies. Le Bourgeois and Marnotte (2002) located this critical period between 15 and 60 DAS for annual short-cycle crops such as rice and other cereals (maize and sorghum). In Ghana, Dzomeku et al. (2007) determined in rainfed condition that the critical period of two varieties of NERICA rice (NERICA1 and NERICA2) was between 21 and 42 DAS. For irrigated rice in the Sahel, this critical period was between 29 and 32 DAS during the rainy season and between 4 and 83 DAS during the dry season (Johnson et al., 2004). In rainfed rice in southern Togo, this critical period was a little shorter, and weed competition was much more harmful between 21 and 30 DAS (Boyoda, 1991).

For both groups of competition (early and late), average yields of the five rice varieties during the two years of experimentation were almost equal to the weed-free plots when plots were unweeded or weeded during the first two weeks (Figure 1). In this case, weeds germinating very early during the crop cycle did not significantly affect yields. In addition, during the early stage of the cropping cycle, weed flora is less developed; making weed controls easier with greater efficiency.

These early weeding controls avoid rhizomes and cuttings of some frequent perennial weeds (*Imperata cylindrica* and *Cyperus* spp) from growing on the experimental site. Weeds with higher relative frequency were annual grasses such as *Digitaria longiflora* and *Dactyloctenium aegyptium* (Table 3). For these annual species with short growth cycle, the early weedings prevent development, flowering, fruiting, and seed production which would increase the seed stock in the

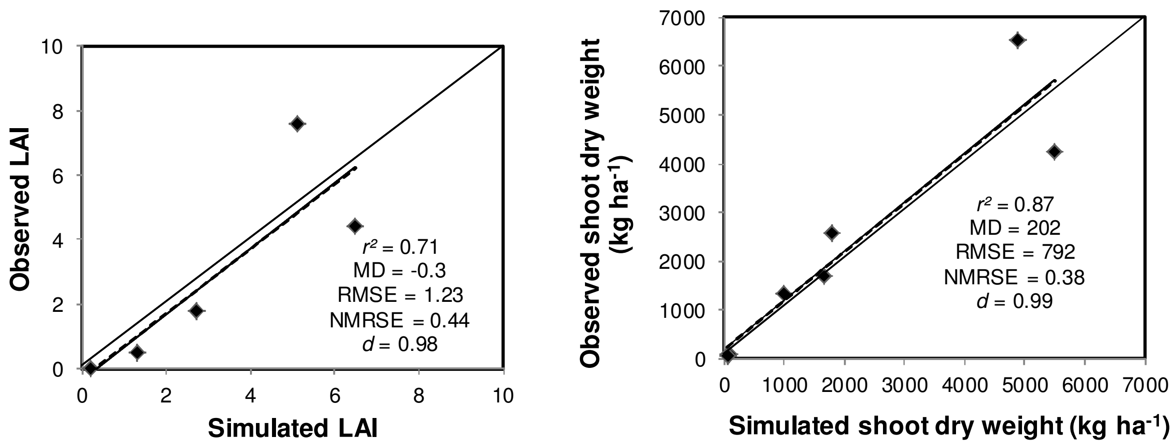

Figure 2. 1:1 scale plot, regression and statistics of observed and INTERCOM-simulated values of rice NERICA1 LAI and shoot dry weight during model calibration.

soil (Akobundu, 1987). The drawback of the early weeding resides in the close resemblance of those grass weeds with rice plants at their seedling and vegetative stage, and those weeds can be mistaken for the rice crop, and thus evade eradication during hand weeding (Akobundu, 1987).

Simulating the effects of the duration of weed competition on crop yields

Model calibration

The calibrated values of AMAX, SLA and SL0 are presented in Table 2. Upon calibration, the model simulations of LAI were reasonably satisfactory early in the crop growth cycle but discrepancies appeared noticeable later during the cycle. Measured and simulated LAI values were fairly well correlated (r^2 = 0.87) and the Willmott's index of agreement (*d*) was 0.98, indicating that simulated and measured data agreed well (Figure 2). However, the mean difference value was -0.3 and the RMSE was 1.23 resulting in a fairly high prediction error of 44% for the measured mean value. Storkey et al. (2003) used an INTERCOM-based eco-physiological model to simulate LAI for a winter wheat crop and reported measured and simulated data with r^2 of 0.69 and 0.72. Our r^2 value of 0.71 was well in the range of their values but they did not report any other statistics. Simulated and measured values of shoot dry weight matched reasonably well early in the crop growth period but were less satisfactory later during the growth period where the model either underestimated or overestimated shoot dry weight (Figure 2). Measured and simulated shoot dry weight values were highly correlated (r^2 = 0.87) and the Willmott's index of agreement (*d*) was 0.99, indicating a good match between simulated and measured data (Figure 2). The mean difference value was 202 kg ha^{-1} and the RMSE was 792 kg ha^{-1} leading to a prediction error of 38% for the measured mean value. Weaver et al. (1992) used the model to simulate dry matter under a tomato crop and found that the model accurately simulated the increase in dry matter, but did not provide any statistics on the comparisons of measured and simulated data sets. Overall, our results during the calibration process showed a generally good match between simulated and observed LAI and shoot dry weight data (r^2 values of 0.71 and 0.87, and *d* values of 0.98 and 0.99), but the 44 and 38% prediction error values for the measured mean values of LAI and shoot dry weight, respectively, indicate that there may be room for improvement of the model simulations.

Model performance

When the calibrated model was tested against measured yield data of 2004, 2005 and pooled yield data from the two years from plots with and without weed infestation, it performed reasonably well. There was a good agreement between measured and simulated values and their trends did not display any noticeable deviations (Figure 3). The data sets were highly correlated with r^2 values ranging from 0.84 to 0.87 and Willmott's index of agreement values in all cases were 0.99. The RMSE values were low (typically between 200 and 240 kg ha^{-1}) with prediction errors ranging from 15 to 19% (Figure 3). The mean difference values were negative in all cases (typically ranging between -50 and -140 kg ha^{-1}) which indicates that in general the model tended, although slightly, to overestimate the yield data. This suggests that the model might underestimate yield losses especially under weed infestation conditions presumably because it assumes that nutrients are not limiting to crop growth. Our findings on the simulation of crop yields corroborate those reported by several other similar studies. Storkey et

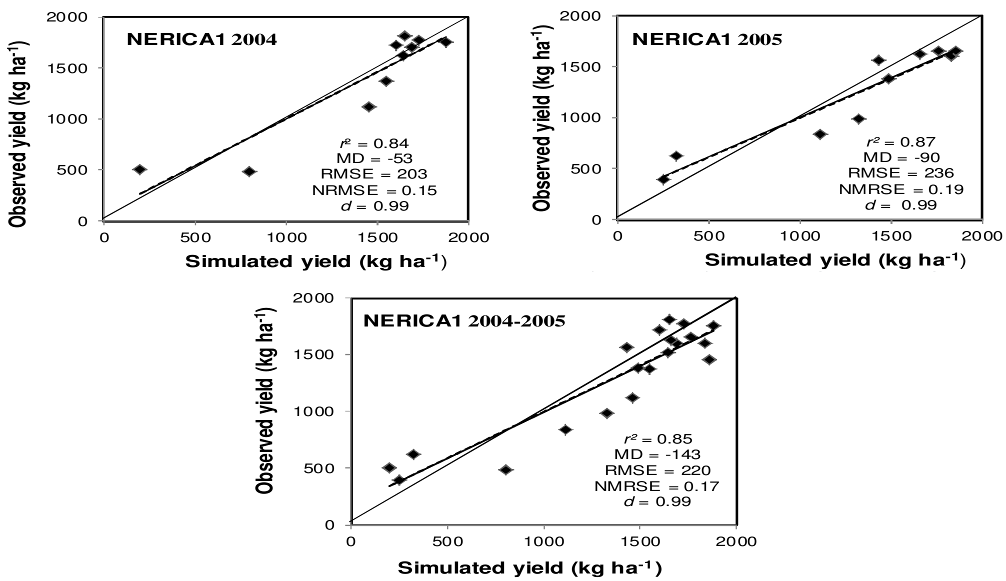

Figure 3. 1:1 scale plot, regression and statistics of observed and INTERCOM-simulated values of rice NERICA1 yield during model performance testing.

al. (2003) used a simple thermal time model and an INTERCOM-based eco-physiological model to simulate winter wheat yield loss and found that both approaches underestimated yield damage coefficient although the eco-physiological model performed better. The simple thermal model was only able to describe a maximum of 55% of the variation in yield loss. Weaver et al. (1992) used the INTERCOM model to simulate yield losses under sugar beets and tomato crops, and reported r^2 values ranging from 0.81 to 0.94 between simulated and observed data. They found that under both crops the model underestimated yield losses when weeds were allowed to compete with the crop for longer than 20 days after transplanting and 45 days after emergence, and argued that these trends in the simulations were linked to the assumption that nutrients were not limiting to crop growth in the model.

Conclusion

Weed flora at the experimental site was variable in composition but grasses were the most dominant flora, followed by sedges. Season-long weed infestation resulted in reduction in grain yields of about 74% in the varieties, suggesting the vulnerability of rice crop to weed infestation. In this study, the critical period of weed competition was approximated for upland rice varieties in southern Mali (14 to 42 DAS), and the harmful effects of early weed competition was demonstrated. Overall, the INTERCOM model proved to be capable of simulating the interactions between NERICA1 rice crop yield losses, weed density, and duration of weed competition under rainfed conditions in northern Guinea savanna agro-ecology in southern Mali. A better and more realistic performance of the model requires further analysis of the assumption that nutrients are not limiting to crop growth, through quantitative field experiments at different levels of nutrients.

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