CRITICAL PERIOD FOR WEED CONTROL IN POTATOES IN THE HUAMBO PROVINCE (ANGOLA)[1]

Período Crítico do Controle de Infestantes na Cultura da Batateira na Província do Huambo (Angola)

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ABSTRACT - The effects of different weed management periods on potatoes were studied in three areas (Bailundo, Chianga and Calenga) of the central highlands of Angola and in three cropping seasons, from June 2005 to May 2007. Six weed-management treatments were used to identify critical periods of competition and to allow the development of more precise management recommendations. Total potato yield ranged from about 22 t ha^{-1} in weed-free plots to about 3 t ha^{-1} with no weed control – a yield loss of 86%. Major weed species – *Galinsoga parviflora*, *Cyperus esculentus*, *Bidens biternata*, *Amaranthus hybridus*, *Nicandra physaloides*, *Portulaca oleracea* and *Datura stramonium* – differed from area to area. The species *G. parviflora* dominated the weed flora in all three areas – 73, 97 and 72 plants m^{-2} 50 days after crop emergence in Bailundo, Chianga and Calenga respectively, in dry season trials; while *C. esculentus* was also present in Chianga and Calenga, with an average density of ca 30 plants m^{-2} in dry season trials. Gompertz and logistic equations were fitted to data representing increasing periods of weed-free growth and weed interference, respectively. Critical periods for weed control, with a 95% weed-free total yield, were estimated from 26 to 66 and from 20 to 61 days after emergence for the rainy and dry seasons, respectively. Weed competition before or after these critical periods had negligible effects on crop yield.

Keywords: *Solanum tuberosum*, tropical Africa, yield loss.

RESUMO - Com o objectivo de obter recomendações mais precisas para a gestão das infestantes na cultura da batata 'Romano' avaliou-se o efeito de diferentes períodos de controle e de convivência em três locais do Planalto Central de Angola e em três épocas de crescimento da cultura. O delineamento experimental, por local, consistiu em blocos casualizados com três repetições. Os tratamentos consistiram de seis intervalos de controle nos quais a cultura foi mantida livre de infestantes e após cada período estas foram deixadas crescer livremente; e de seis períodos de convivência, nos quais a cultura foi mantida na presença das infestantes e após cada período estas foram eliminadas até à colheita. Os períodos de controle e convivência para determinar o início do período crítico foram 20, 30, 40, 50, 60 dias após emergência da cultura (DAE), e até colheita, além de uma testemunha sempre limpa e outra sempre com a presença de infestantes. A produção total de batata variou entre cerca de 22 t ha^{-1} na testemunha livre de infestantes e 3 t ha^{-1} na testemunha sempre com infestantes – uma perda na produção de 86%. Foram identificadas 15 famílias e 51 taxa. As famílias dominantes foram Asteraceae (30%), Fabaceae (18%), Poaceae (12%) e Solanaceae (6%). As principais espécies – ***Galinsoga parviflora***, ***Cyperus esculentus***, ***Bidens biternata***, ***Amaranthus hybridus***, ***Nicandra physalodes***, ***Portulaca oleracea*** *e* ***Datura stramonium*** *– diferiam na sua abundância de local para local. A espécie* ***G. parviflora*** *era dominante nos três locais de estudo – 73, 97 e 72 plantas m^{-2} 50 DAE no Bailundo, Chianga e Calenga, respectivamente, na estação seca; enquanto* ***C. esculentus*** *esteve sempre presente na Chianga e na Calenga, com uma densidade média de ca*

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30 plantas m^{-2} na estação seca. As equações do modelo exponencial foram ajustadas aos dados de biomassa seca de infestantes enquanto que as equações de Gompertz e a logística foram ajustadas aos dados de produção de batata obtidas nos períodos crescentes de controle e períodos de convivência estudados, respectivamente. Os períodos críticos, para uma perda na produção de 5%, foram de 26 a 66 e de 20 a 61 DAE para a estação das chuvas e da seca, respectivamente. Em síntese, em Angola (Plantalto Central) o início e o fim do período crítico variaram com a época de cultura da batata. O período de prevenção da interferência foi de 40 e 41 dias para a época das chuvas e da seca (regadio), respectivamente.

Palavras-chave: *Solanum tuberosum*, produção, África tropical.

INTRODUCTION

The potato (*Solanum tuberosum*) is one of the main components of the agro ecosystem in the central highlands of Angola, and according to surveys carried out between 2004 and 2007, both yield and cropping areas have increased slightly in recent years (Henriques, 2008). According to a FAO (2007) report, in the 2005/06 growing season, 499,344 ha of potatoes were cultivated in Angola, with an average yield of 4.1 t ha^{-1}. Of this total, 128,220 ha were in the Huambo region, with an average yield of 4.7 t ha^{-1}. Such yield levels are lower than those recorded for Africa as a whole (Oerke & Dehne, 2004). Nevertheless, potato consumption is increasing in Angola and this has resulted in the need for substantial potato imports. Of the total volume of potatoes consumed in Angola (1,300,000 t), about 60% is imported, mainly from South Africa, Namibia and the Republic of Congo (FAO, 2007).

A parallel research in the Huambo region showed that the quality of seed potatoes, soil fertilization and the management of pests, diseases and weeds are factors that have limited potato yield to a large extent (Henriques, personal communication). The yield losses due to pests and diseases are either a consequence of a low level of knowledge about pesticide selectivity, or due to poverty, which has limited the farmers' acquisition of the appropriate pesticide. In the Huambo region, weed control in potatoes is generally done manually, which is expensive due to high manpower requirements, and most of the times not effective due to inappropriate timing of weed control. Surveys carried out during 2005 and 2007 revealed that small potato-farmers did not apply any herbicides (Henriques, personal communication). It is not uncommon to have two or three weedings between planting and harvesting, but without considering weed density or the crop-growing cycle.

The timing of weed removal after determining the critical weed control period is an important component of integrated weed management in crop production systems (Portugal & Vidal, 2009). Critical periods of weed-crop competition for potatoes have been determined in a few environments, and only for some weed species (Saghir & Markoullis, 1974; Nelson & Thoreson, 1981; Thakral et al., 1989; VanGessel & Kenner, 1990; Baziramakenga & Leroux, 1998; Ciuberkis et al., 2007; Costa et al., 2008). In general, the critical period for weed removal in potatoes was about 4 and 6 weeks after planting, but Costa et al. (2008) reported that, in Brazil, the critical period for weed interference was just one day, from 20 to 21 days after tuber planting. In the UK, a single weeding between 2 and 8 weeks after crop planting was enough to prevent significant yield loss. Weeds that emerged later were generally suppressed by the crop if the canopy cover by potatoes was 100%, but with a lower canopy cover the weed removal at 2 weeks after planting was not effective, inasmuch as weeds that emerged subsequently were still able to compete with the crop (Turner et al., 1999). Weeds could be left for up to 9 weeks after potato planting without causing any yield loss at harvest (Saghir & Markoullis, 1974). Lopes (1989), in a study with crop plantation densities of 2, 4 and 8 tubers m^{-2}, achieved good weed control with a single application of a mixture of two residual herbicides carried out one week after plantation. Soil coverage by potatoes was 100%, and marketable productions ranged between 38.8, 48.7 and 57.6 t ha^{-1}. In Canada, keeping plots weed-free for 3 weeks was not sufficient to prevent some reduction in yield. Competition from *Elytrigia repens* began soon after crop emergence when infestations were severe and at 15 days after crop emergence when couch numbers were low (Baziramakenga & Leroux, 1994). However, due to the diversity of climatic conditions, weed species and management techniques, these studies are site specific and cannot be extrapolated to other environments, especially tropical African countries.

The objective of the present research was to determine the critical period for weed control in potatoes in the Huambo province, which is located in the Central highlands of Angola, so as to rationalize and optimize the labour input required for weed control in the production of this crop in the area.

MATERIAL AND METHODS

Field experiments were conducted over a two-year period from June 2005 until September 2007, at three sites in the Huambo Province, Bailundo, Chianga and Calenga (Table 6). This area is located in the central highlands of Angola, with an area of 29,827 km^2, and has two seasons – rainy and dry – per year, with trade winds. Due to the altitude, the climate is warm-temperate, with an average annual temperature of less than 20 °C (Diniz, 1991) and average annual rainfall of about 1,200 mm (Table 1).

All three locations are within about 50 km of each other, but have different soil conditions. The Bailundo study was located in a farmer's field at 12° 12' 95" S, 15° 49' 21" E and an altitude of 1,749 m, with a sandy loam soil (70% sand, 14% silt, 16% clay) with 0.68% OM and a pH of 5.5. The Chianga study was located at the Chianga Experimental Agricultural Station (12° 44' 37" S, 15° 49' 62" E), at an altitude of 1,698 m. The plots were established on a clay soil (6% sand, 35% silt, 59% clay) with 2.24% organic matter (OM) and a pH of 5.2. The Calenga study was also located in a farmer's field at an altitude of 1,732 m altitude and at 12° 56' 86" S, 15° 26' 83" E, on a clay soil (35% sand, 25% silt, 40% clay) with 1.4% OM and a pH of 5.5. More detailed descriptions of the soils can be found in MJIU (1961), Nogueira (1970) and Asanzi et al. (2006).

The two-year field trials were conducted at each location in three cropping seasons per year: two during the rainy season – the first from October to January, and the second from February to May – and the third during the dry season (irrigation time), from June to September (Table 6). In each season, the land was ploughed (35 cm depth) and harrowed (25 cm depth), and the weeds were removed by hand hoeing. In accordance with the results of previous studies (Asanzi et al., 2006; Henriques et al., 2010), fertilizer was calculated to provide 100, 200 and 100 kg ha^{-1} of N, P_2O_5 and K_2O respectively, applied and incorporated into the soil using a cultivator before potato planting. Ammonium sulphate (475 kg ha^{-1}, which provided 100 kg N ha^{-1}) was applied approximately 20 days after potato emergence. During the third cropping season, water was supplied to the plot area by furrow irrigation throughout the crop growing season.

Each plot size was 3.2 m wide and 5 m long, and consisted of six potato rows. The middle four rows of each plot (8 m^2) were used for data collection. The potato cv. 'Romano' from

Table 1 - Monthly rainfall during the 2005, 2006, and 2007 potato growing cycles, average monthly rainfall from 1994 to 2004 recorded at the Chianga Experimental Agriculture Station (Angola)

Month	Precipitation (mm)			
	2005	2006	2007	1994-2004
January	212	120	194	181
February	238	163	168	163
March	268	221	212	213
April	142	133	136	151
May	0	0	0	7
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	13
October	233	207	213	113
November	202	225	236	181
December	211	259	279	215
Total	1,506	1,328	1,438	1,237

AGRICO (Emmeloord, Holland) was hand-planted in rows spaced 20 cm apart, with 80 cm in between rows – i.e. with a planting density of 6.25 tubers m^{2}. Plantation and crop emergence dates are presented in Table 6. The experimental design was a randomized complete block with three replications. Two types of weed interference treatment were applied, starting at crop emergence. In order to evaluate the onset of the critical period for weed removal, plots were left weedy for 20 (WI_{20}), 30, 40, 50, 60 days after crop emergence (DAE), and until harvest (WI_{harv}). To determine the end of the critical period, plots were kept weed-free for 20 (WF_{20}), 30, 40, 50, 60 DAE, and until harvest (WF_{harv}). In these treatments, weed-free means the period during which weeds were removed at ten-day intervals. Weed growth was controlled during the required periods for each of the above treatments, and hand-weeding was undertaken.

Naturally occurring weed populations were used in all the trials. Weed infestation was evaluated in two random 0.25 m^2 quadrates per plot at 20, 30, 40, 50, 60 DAE, and at harvest (after 95 DAE in the rainy season, and after 110 DAE in the irrigation period), with plants being cut at ground level. Weed species density and above-ground dry weights at 65 ºC were recorded. The crop variables recorded included crop emergence (Table 6), crop soil coverage, weight of total and marketable tubers (tuber diameter greater than 25 cm), and without symptoms of disease. Sampling was done in the two central rows of each plot, thereby giving a final determination for an area of 8 m^2. On a per-plot basis, weed measurements were transformed to m^{-2} and crop measurements to t ha^{-1}.

Analysis of the variance of the combined weed density and weed biomass data indicated significant treatment-by-location and treatment-by-season interactions for all variables, so the data were analysed separately for each location and for the rainy and dry growing seasons.

In order to determine the type of relationship between weed dry weight and all treatments, an exponential curve was fitted to the series of weed-free treatments (Sit & Costello, 1994; Bukun, 2004):

$$Y = ae^{bx}$$

where, Y is the weed dry weight (g m^{-2}), a the y-intercept, b the asymptote of the curve, and x the length of weed-free period (in DAE). Schumacher's (1939) model, as used and described by Bukun (2004), was fitted to the weed-infested treatment and weed biomass accumulation:

$$Y = e^{a+b/x}$$

where, Y is the weed dry weight (g m^{-2}), a the maximum weed biomass, b the asymptote of the curve, and x the duration of weed infested period (in DAE).

Total and marketable yields and relative yields were subjected to an overall analysis of variance that revealed no significant differences between years or between the first and second cropping rainy season's values. The average yield values for these two cropping seasons were thus used in further statistical analysis. The significance of year/location/season and treatment combinations was evaluated at a probability level of P=0.05%. The relative yield for each treatment was calculated as a percentage of the corresponding weed-free yield. The significance of interaction between year, location, climatic season and treatment combinations was evaluated at a probability level of P=0.05%. Because the ANOVA indicated a significant treatment-by-season interaction, the data are therefore presented separately for the rainy (average of the two rainy cropping seasons) and dry seasons.

The three-parameter Gompertz model was used to predict the relationship between relative yields, as influenced by the increasing length of the weed-free period (WF_{20}-WF_{harv}) (Equation 1); the three-parameter logistic regression model was used to describe the influence of the increasing duration of the weed-infested period (WI_{20}-WI_{harv}) on potato yield (Equation 2). The form of the Gompertz equation used was:

$$Y=a*\exp(-\exp(-(x-x_0)/b)) \qquad \text{(Equation 1)}$$

where, Y is the estimated potato yield (% of weed-free crop yield); x is the time expressed in days after emergence; a is the theoretical maximum yield; x_0 is yield as time equals zero; and b represents the slope. The form of the logistic equation used was:

$$Y = a/[1+(x/x_0)^b] \quad \text{(Equation 2)}$$

where, Y is the predicted potato yield (% of weed-free crop yield); x is the duration in days of weed interference from crop emergence; and a, b and x_0 are constants.

In order to determine the critical period for weed control, three yield-loss levels – 2.5% 5% and 10% – were chosen arbitrarily. The onset and end of the critical period were determined by substituting the yield-loss level in the logistic and Gompertz equations, respectively.

The Statistix 8 software (Analytical Software, Tallahassee, FL) was used to perform the ANOVA. The non-linear regressions and figures were produced with SigmaPlot 9.1 (Systat Software Inc., Point Richmond, CA).

RESULTS AND DISCUSSION

In the rainy and dry seasons, the weed community in the experimental plots was composed of 51 different species belonging to 15 families. The dominant ones were Asteraceae (30%), Fabaceae (18%), Poaceae (12%) and Solanaceae (6%).

Weeds growing in the unweeded experimental plots showed the highest density at 50 DAE (Table 2; Table 3). *Galinsoga parviflora*, *Bidens biternata*, *Amaranthus hybridus*, *Nicandra physalodes*, *Portulaca oleracea* and *Datura stramonium* (absent in Bailundo) were the dominant species in both seasons and at all three locations. There were no significant differences in the average density of the major weed species between the rainy and dry seasons. Annual weeds formed approximately 90% of all weeds observed in both seasons. Some perennial species (e.g. *Cyperus esculentus*) presented high densities in both growing seasons in Chianga and Calenga. The dominant species in Bailundo were *G. parviflora*, *B. biternata*, *A. hybridus*, *N. physalodes* and *P. oleracea*; in Chianga they were *C. esculentus*, *B. biternata*, *N. physalodes*, *D. stramonium* and *P. oleracea*; and in Calenga the species with the highest density were *C. esculentus*, *B. biternata*, *A. hybridus* and *G. parviflora*.

Table 2 - Average density (plants m^{-2}) of main weed species in unweeded controls measured at 20 and 50 days after crop emergence during the rainy season at the three locations. (The details of experiments are shown in Table 6)

Species	Rainy season					
	Bailundo		Chianga		Calenga	
	20 DAE	50 DAE	20 DAE	50 DAE	20 DAE	50 DAE
Amaranthus hybridus L.	13.3 (3.74)	30.8 (1.20)	15.7 (2.44)	24.8 (4.67)	10.8 (2.94)	25.0 (4.74)
Bidens biternata (Lour.) Merr. & Scherff	5.5 (3.76)	38.0 (4.57)	8.2 (4.25)	41.0 (3.89)	10.5 (4.52)	40.5 (3.39)
Chamaecrista mimosoides (L.) Greene	2.0 (0.97)	2.3 (1.09)	0.3 (0.21)	3.5 (1.62)	0.7 (0.33)	2.2 (1.97)
Chenopodium ambrosioides L.	2.8 (1.80	3.3 (1.52)	0.8 (0.54)	6.3 (2.28)	-	-
Cynodon dactylon (L.) Pers.	5.5 (3.19)	3.3 (2.12)	2.8 (1.28)	5.7 (2.57)	6.3 (2.55)	9.0 (3.20)
Cyperus esculentus L.	-	-	19.8 (4.60)	18.5 (4.78)	19.0 (4.52)	15.0 (6.85)
Cleome iberidella Welw. ex Oliv.	6.7 (1.45)	7.7 (2.58)	5.7 (2.72)	6.3 (2.69)	3.2 (1.64)	3.7 (1.33)
Datura stramonium L.	-	-	13.3 (5.46)	16.7 (3.85)	5.7 (2.25)	13.0 (3.50)
Eleusine indica (L.) Gaertn.	2.5 (0.67)	7.3 (2.83)	1.8 (0.3)	7.2 (2.7)	0.2 (0.17)	1.2 (0.48)
Galinsoga parviflora Cav.	24.8 (7.77)	73.3(12.08)	41.2 (8.68)	98.7 (5.83)	31.8 (9.09)	58.3 (3.86)
Ipomea eriocarpa R. Br.	4.2 (0.54)	7.2 (2.15)	-	-	2.5 (0.76)	7.3 (2.84)
Melinis repens (Willd.) Zizka	2.2 (0.31)	7.3 (3.02)	3.0 (0.86)	9.5 (3.86)	2.2 (0.31)	7.6 (2.62)
Nicandra physalodes (L.) Gaertn.	13.7 (3.5)	16.7 (2.17)	16.5 (3.01)	17.5 (3.01)	12.2 (2.52)	18.5 (3.30)
Portulaca oleracea L.	9.5 (2.81)	11.3 (2.33)	11.2 (1.62)	12.2 (3.91)	5.5 (1.73)	7.5 (2.43)
Subtotal	92.7	208.9	140.3	268.7	110.6	208.8
Other *taxa**	50.0	77.4	81.4	104.7	121.6	103.2
Total	142.5 (28.12)	286.3 (27.78)	221.7 (24.26)	373.4 (44.92)	232.4 (14.69)	312.0 (42.70)

Each value represents the mean plant density and standard errors of 12 measurements. * Average density of 35 *taxa* that were also surveyed in potato plots.

Table 3 - Average density (plants m^{-2}) of main weed species in unweeded controls measured at 20 and 50 days after crop emergence during the dry season at the three locations (The details of experiments are shown in Table 6)

Species	Dry season					
	Bailundo		Chianga		Calenga	
	20 DAE	50 DAE	20 DAE	50 DAE	20 DAE	50 DAE
Amaranthus hybridus L.	9.8 (2.50)	20.7 (7.61)	10.2 (3.02)	26.8 (4.06)	11.8 (3.44)	11.8 (6.5)
Bidens biternata (Lour.) Merr. & Scherff	6.5 (3.42)	32.3 (5.0)	9.3 (5.63)	26.0 (8.90)	5.3 (2.94)	30.3 (4.13)
Chamaecrista mimosoides (L.) Greene	1.7 (1.12)	5.8 (5.3)	1.3 (1.15)	1.83 (1.33)	3.5 (1.29)	9.0 (5.72)
Chenopodium ambrosioides L.	2.3 (1.33)	3.2 (2.61)	-	4.5 (2.92)	-	-
Cynodon dactylon (L.) Pers.	0.8 (0.83)	4.0 (2.84)	3.3 (1.99)	4.7 (3.4)	13.5 (5.09)	24.8 (11.2)
Cyperus esculentus L.	-	-	6.2 (4.25)	26.7 (6.65)	24.2 (6.29)	26.5 (9.19)
Cleome iberidella Welw. ex Oliv.	6.8 (2.63)	6.2 (2.46)	3.7 (2.39)	9.7 (5.82)	5.8 (2.50)	6.3 (3.52)
Datura stramonium L.	-	-	7.0 (3.75)	17.3 (3.94)	12.0 (4.16)	13.2 (5.88)
Eleusine indica (L.) Gaertn.	1.8 (0.40)	2.5 (1.63)	1.2 (0.54)	4.7 (3.35)	0.3 (0.23)	0.5 (0.34)
Galinsoga parviflora Cav.	22.7 (6.76)	72.7 (11.55)	37.7 (9.79)	97.3 (10.65)	20.3 (9.92)	72.0 (17.86)
Ipomea eriocarpa R. Br.	3.7 (1.12)	4.3 (2.12)	-	-	3.5 (1.86)	5.8 (5.64)
Melinis repens (Willd.) Zizka	3.5 (1.65)	4.3 (2.12)	1.7 (0.49)	4.3 (2.12)	3.2 (1.30)	9.7 (4.50)
Nicandra physalodes (L.) Gaertn.	11.2 (2.52)	17.3 (1.91)	13.5 (3.68)	15.2 (4.19)	21.3 (6.78)	14.7 (4.43)
Portulaca oleracea L.	12.0 (5.31)	7.8 (2.69)	11.8 (4.70)	17.2 (6.58)	14.3 (3.55)	14.0 (5.25)
Subtotal	82.8	181.1	106.9	256.23	139.0	238.6
Other *taxa**	58.5	113.9	126.6	107.07	167.2	157.1
Total	141.3 (35.84)	295.0 (37.94)	233.5 (38.48)	363.3 (34.4)	306.2 (35.72)	395.7 (56.96)

Each value represents the average values and standard errors of 6 measurements. * Average density of 35 *taxa* that were also surveyed in potato plots.

Total biomass (g m^{-2} dry weight) of weeds increased at all the locations and in all the growing seasons, as the duration of the weed-infested period increased and decreased with the increasing duration of the weed-free period (Figure 1; Figure 2). Responses were highly significant (as identified by the R^2 values) in relation to both growing seasons and locations (Table 4; Table 5).

The weed analyses highlighted the species' richness – more than 50 *taxa* per field experiment – and the importance of annual weeds, which formed approximately 90% of all weeds observed. This complex weed situation is typical in sub-humid tropical organic farming, where weeds are the major pest, and are coupled with inefficient weed control practices (Akobundu, 1991). The high species diversity is also in accordance with other (long-term) studies conducted in organic farming systems, and is due to the low intensity of the farming system (Hiltbrunner et al., 2008).

Nevertheless, the importance of weed species varied from one location to another. These inter-location differences in weed composition can be attributed to different soil textures at the three experimental locations. The perennial weed species *C. esculentus* is becoming an important component of the weed population in the clay soils of the Chianga and Calenga field experiments in both rainy and dry seasons. This troublesome and competitive weed may be problematic in this organic farming situation. Preventive practices that reduce the establishment of *C. esculentus* in potato fields must be given high priority.

Potato soil coverage by year, location and growing season was always partial, at about 80 (±5)% of the area, even considering that potato planting density was high (6.25 tubers m^{-2}). Average tuber emergence was 5.5 (±0.25) tubers m-^{2} (data not shown).

By year, location and growing season, total potato and marketable yields ranged from 18.7 to 24.1 and from 16.6 to 20.9 t ha^{-1} on the weed-free plots; while on the weeded plots total yields varied between 1.9 and 3.3 t ha^{-1} and marketable yields ranged between 1.2 and 2.2 t ha^{-1} (Table 6).

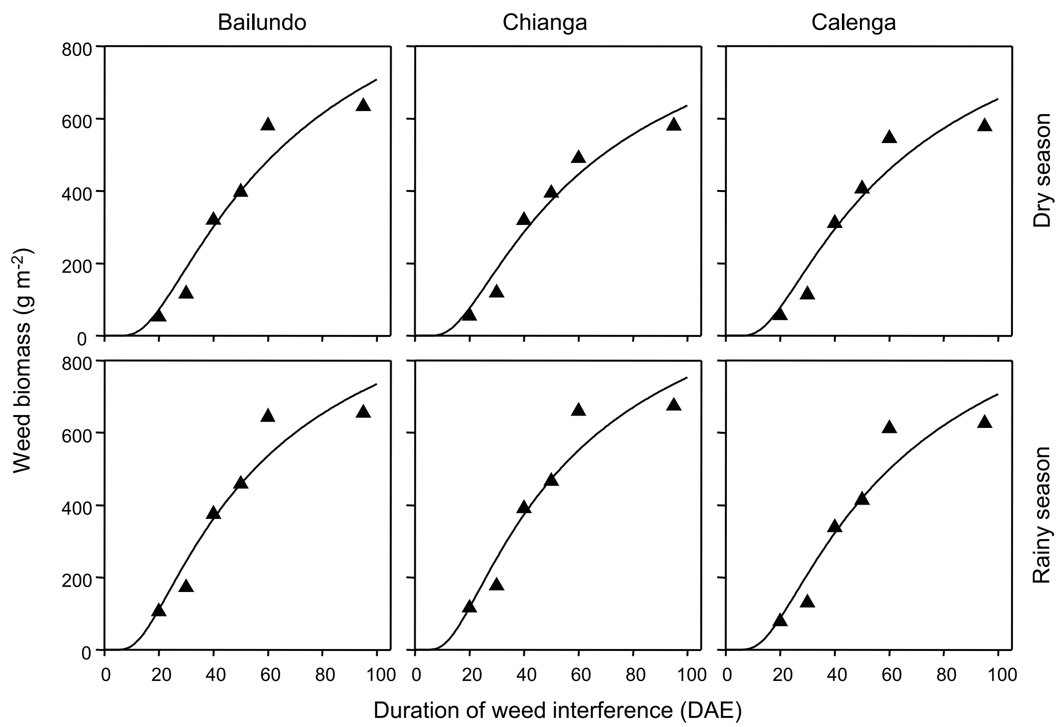

Figure 1 - Effects of increasing duration of weed interference on weed biomass (dry-weight, g m^{-2}) accumulation at Bailundo, Chianga and Calenga in the dry and rainy seasons. Dots indicate observed data (average values of 6 and 12 measurements in dry and rainy seasons, respectively). DAE, Days after crop emergence. The parameters for fitted curves are provided in Table 4.

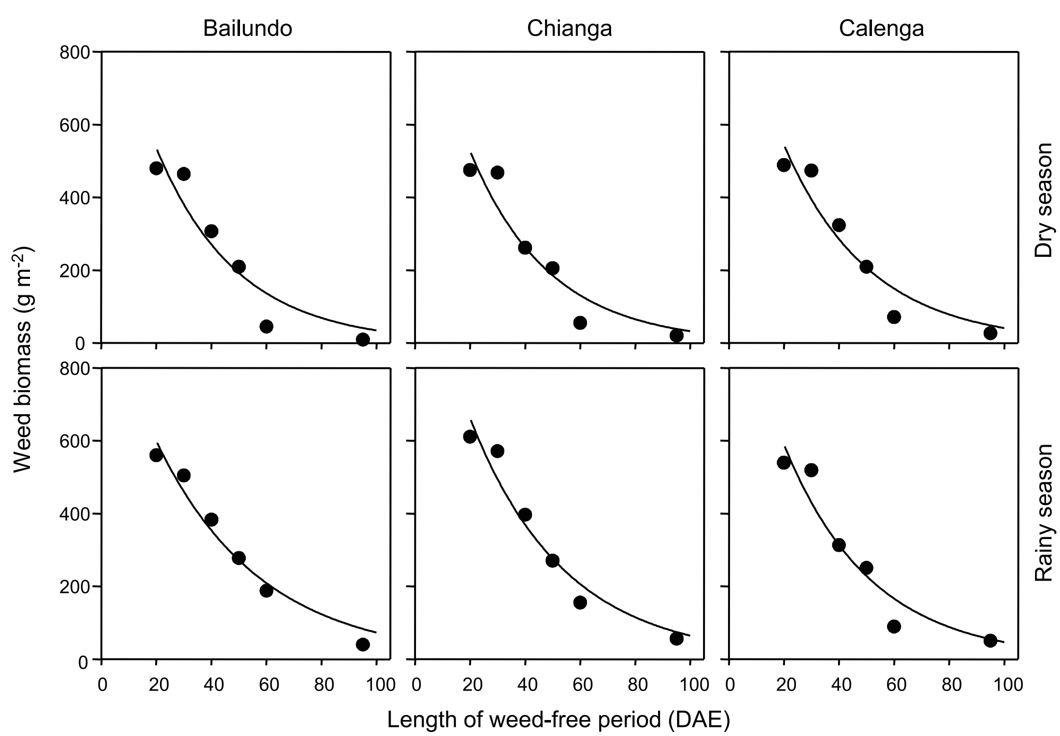

Figure 2 - Effects of increasing length of weed-free period on weed biomass (dry-weight, g m^{-2}) accumulation at Bailundo, Chianga and Calenga in the dry and rainy seasons. Dots indicate observed data (average values of 6 and 12 measurements in dry and rainy seasons, respectively). DAE, Days after crop emergence. The parameters for fitted curves are provided in Table 5.

Predicted and observed total and marketable yields, as affected by the action of the weed-infested or weed-free period in the rainy and dry seasons, are illustrated in Figure 3. Parameters for the equations depicting the critical weed-free period and the critical time for weed removal in the potato are summarized in Tables 7 and 8, respectively.

Total and marketable yields responded to treatments in similar patterns. Early weed interference affected crop yield. Yields, both total and marketable, of potato plants grown with weeds decreased with prolonged delays in weed removal in all treatments, in both the rainy season and the dry season. Conversely, in all treatments potato yields rose with

Table 4 - Effects of increasing duration of weed interference on weed biomass (dry-weight, g m^{-2}) accumulation at Bailundo, Chianga and Calenga in the dry and rainy seasons - parameter values for response curves of Figure 1 based on exponential model $Y = e^{a + b/x}$

Season/Local	*a*	*b*	R^2
Dry season			
Bailundo	7.14 (0.179)	-57 (10.5)	0.93
Chianga	6.99 (0.140)	-53 (8.0)	0.96
Calenga	7.02 (0.185)	-53 (10.6)	0.92
Rainy season			
Bailundo	7.07 (0.167)	-47 (9.2)	0.92
Chianga	7.09 (0.165)	-47 (9.1)	0.92
Calenga	7.08 (0.194)	-52 (11.1)	0.91

Values in parentheses are standard errors of parameters.

Table 5 - Effects of increasing length of weed-free period on weed biomass (dry-weight, g m^{-2}) accumulation at Bailundo, Chianga and Calenga in the dry and rainy seasons - parameter values for response curves of Figure 2 based on exponential model $Y = ae^{bx}$

Season/Local	*a*	*b*	R^2
Dry season			
Bailundo	1063 (275.1)	-0.0342 (0.0084)	0.90
Chianga	1058 (262.4)	-0.0348 (0.0081)	0.90
Calenga	1039 (234.5)	-0.0323 (0.0072)	0.91
Rainy season			
Bailundo	1014 (116.4)	-0.0263 (0.0034)	0.97
Chianga	1187 (174.9)	-0.0292 (0.0045)	0.95
Calenga	1111 (226.4)	-0.0316 (0.0064)	0.92

Values in parentheses are standard errors of parameters.

Table 6 - Details of experiments - year, location, growing season, crop plantation date and emergence - and total and commercial potato (*Solanum tuberosum* L.) yield (t ha^{-1}) recorded in the unweeded and weeded plots 95 days after crop emergence

Year	Local	Growing season	Crop plantation date	Crop emergence	Unweeded plots		Weeded plots	
					Total yield (t ha^{-1})	Marketable yield (t ha^{-1})	Total yield (t ha^{-1})	Marketable yield (t ha^{-1})
2005/2006	Bailundo	Dry season	15 June 2005	1 August 2005	19.6 (0.60)	16.6 (0.46)	2.9 (0.12)	1.9 (0.06)
		1st Rainy season	12 October 2005	27 October 2005	24.1 (1.62)	20.9 (2.02)	1.9 (0.02)	1.2 (0.07)
		2nd Rainy season	4 February 2006	19 February 2006	22.6 (1.93)	20.4 (1.73)	2.3 (0.25)	1.4 (0.20)
	Chianga	Dry season	25 June 2005	10 August 2005	19.9 (0.30)	16.9 (0.55)	3.0 (0.12)	1.8 (0.06)
		1st Rainy season	17 October 2005	1 November 2005	21.3 (1.44)	18.4 (1.63)	2.3 (0.45)	1.4 (0.27)
		2nd Rainy season	8 February 2006	23 February 2006	20.1 (0.32)	17.3 (0.85)	2.3 (0.34)	1.5 (0.29)
	Calenga	Dry season	18 June 2005	3August 2005	19.5 (0.30)	17.8 (0.22)	2.7 (0.32)	1.8 (0.34)
		1st Rainy season	21 October 2005	5 November 2005	20.9 (0.74)	18.2 (1.42)	2.1 (0.16)	1.2 (0.11)
		2nd Rainy season	11 February 2006	26 February 2006	20.7 (0.92)	18.0 (0.99)	2.0 (0.38)	1.3 (0.28)
2006/2007	Bailundo	Dry season	13 June 2006	8 August 2006	19.1 (0.12)	17.1 (0.68)	2.8 (0.23)	1.7 (0.12)
		1st Rainy season	10 October 2006	25 October 2006	20.2 (0.48)	17.9 (0.44)	3.3 (0.17)	2.2 (0.11)
		2nd Rainy season	4 February 2007	19 February 2007	22.7 (2.03)	20.3 (1.90)	2.9 (0.48)	1.8 (0.53)
	Chianga	Dry season	21 June 2006	7 August 2006	18.7 (0.24)	17.3 (0.30)	2.3 (0.40)	1.5 (0.31)
		1st Rainy season	20 October 2006	3 November 2006	19.4 (0.57)	16.7 (0.75)	3.1 (0.31)	2.0 (0.29)
		2nd Rainy season	6 February 2007	21 February 2007	20.3 (0.68)	17.5 (1.21)	3.2 (0.53)	2.1 (0.41)
	Calenga	Dry season	16 June 2006	31 July 2006	18.7 (0.32)	17.4 (0.59)	2.5 (0.27)	1.8 (0.37)
		1st Rainy season	11 October 2006	26 October 2006	20.1 (0.53)	17.4 (1.10)	3.2 (0.27)	2.2 (0.31)
		2nd Rainy season	10 February 2007	25 February 2007	20.9 (1.10)	18.6 (1.30)	2.4 (0.58)	1.8 (0.49)

Values in parentheses are standard errors of 3 measurements.

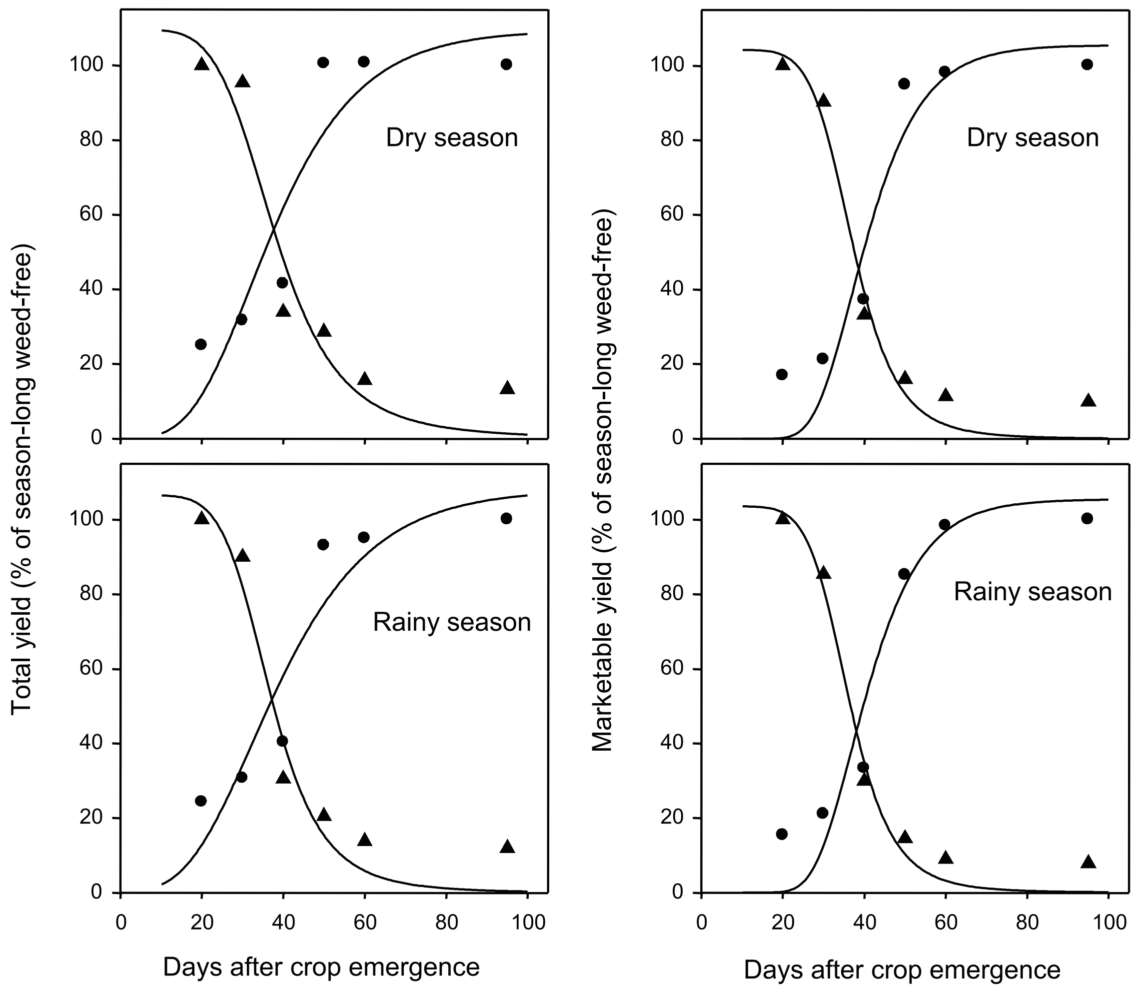

Figure 3 - Effect of weed interference on total and marketable potato yield. Increasing duration of weed interference (triangles) and fitted curves as calculated by the logistic equation; increasing weed-free period (dots) and fitted curves as calculated by the Gompertz equation. The parameters for fitted curves are provided in Table 7.

Table 7 - Effect of weed interference on total and marketable potato yield - parameter estimates for Figure 3 with standard errors (in parentheses) of the models used to calculate the critical periods of weed control from experiments 2005-2007 in the Huambo Province in Angola (potato yields expressed as % of weed free controls)

Yield	Weather season	a	b	x_0	R^2
Duration of weed interference using logistic model $Y = a/[1+(x/x_0)^b]$					
Total	Rainy season	106.5 (14.83)	5.8 (2.23)	36.9 (3.34)	0.95
	Dry season	109.6 (19.86)	4.9 (2.18)	30.0 (4.89)	0.93
Marketable	Rainy season	103.6 (8.42)	6.9 (1.68)	36.3 (1.80)	0.98
	Dry season	104.3 (10.17)	6.9 (2.09)	37.2 (2.23)	0.97
Duration of weed-free period using the Gompertz model $Y=a*\exp\{-\exp[-(x-x_0)/b]\}$					
Total	Rainy season	108.1 (18.52)	16.2 (7.89)	32.3 (5.18)	0.88
	Dry season	109.5 (20.28)	14.7 (8.16)	31.8 (5.51)	0.85
Marketable	Rainy season	105.8 (13.66)	10.5 (4.55)	37.9 (3.31)	0.93
	Dry season	105.5 (14.26)	9.3 (4.56)	37.0 (3.39)	0.91

increase in the duration of the weed-free period. Highly significant ($P < 0.001$) differences between treatments were found in both seasons. The rainy-season experiments with the weed-free treatment (WF_{harv}) gave total and marketable yields of 21.1 and 18.5 t ha^{-1}, compared to 2.6 and 1.7 t ha^{-1} without weed control (WI_{harv}) – reductions of 88% and 91%, respectively. In the dry-season experiments the weed-free treatment (WF_{harv}) gave total and marketable yields of 19.2 and 17.2 t ha^{-1}, compared to 2.7 and 1.7 t ha^{-1} without weed control (WI_{harv}) – reductions of 86% and 90%, respectively.

With potatoes, the onset of the critical period increased as the predetermined yield loss level increased from 2.5% to 10% The maximum weed-infested period was 26 (±2) and 20 (±8) DAE at a 5% total yield loss level, for the rainy and dry seasons respectively (Table 8). The end of the critical period decreased as the predetermined yield loss level increased from 2.5% to 10% (Table 8). The minimum weed-free period ranged from 61 to 66 DAE at a 5% total yield-loss level, depending on the season.

The effects of weed interference throughout the growth of the crop (WI_{harv}) reduced total and marketable crop yields to a very similar extent in the two seasons. Most of the previous studies reported lower yield losses when weeds competed throughout the season (Saghir & Markoullis, 1974; VanGessel & Renner, 1990; Baziramakenga & Leroux, 1998; Ciuberkis et al., 2007). The low fertility of the soils in the region is well documented (Asanzi et al., 2006), but considering the high amounts of fertilizers applied during the study, the reasons that affected potato tuber number and growth, or possibly the number of active haulms per plant (data not recorded) could be various – e.g. nitrogen lixiviation, soil erosion (Edwards et al., 2000; Oliveira, 2000; Döring et al., 2005). Nevertheless, comparing the total potato yields recorded in the weed-free plots (*ca* 20 t ha^{-1}) to the average potato yield in the Huambo Province (4.7 t ha^{-1}), improved crop fertilization and controlling diseases and weeds led to approximately 400% of increase in yield. In another studies in the Huambo Province, on the diseases control and the effects of phosphorus fertilization on potato productivity, similar potato yields were achieved (Henriques et al., 2009, 2010).

Table 8 - Details of the critical periods of weed control for potato for three arbitrarily assigned % yield loss values (2.5%, 5% and 10%)

Crop Yield	Weather season	Time (DAE*) for indicated percentage yield loss		
		2.5%	5%	10%
Onset of critical period from the logistic equation				
Total	Rainy season	24 (8)	26 (8)	28 (8)
	Dry season	20 (8)	20 (8)	22 (8)
Marketable	Rainy season	24 (8)	25 (8)	27 (7)
	Dry season	25 (7)	27 (7)	28 (6)
End of critical period in potato from the Gompertz equation				
Total	Rainy season	69 (1)	66 (2)	60 (3)
	Dry season	64 (2)	61 (4)	56 (4)
Marketable	Rainy season	64 (1)	61 (3)	57 (3)
	Dry season	61 (2)	58 (3)	54 (4)

* DAE, days after crop emergence. Values in parentheses are standard errors of parameters.

The maximum weed-infested period was 26 and 20 DAE at a 5% total yield loss level, for the rainy and the dry seasons, respectively. The minimum weed-free period ranged from 61 to 66 DAE at a 5% total yield-loss level, depending on the season. Weed presence early in the season – 20 days after crop emergence – was thus not detrimental to full yield. Our results match those reported by Saghir & Markooulis (1974), but not those presented by Costa et al. (2008).

In order to avoid total yield losses above 5%, the potato crop therefore requires an average of 41 and 40 days of weed-free maintenance when cropping occurs in the dry and the rainy seasons, respectively. For marketable crop yield, the weed-free period needed to avoid losses above 5% was 31 and 36 days in the dry and rainy seasons respectively.

One of the fundamental principles of weed management is the need for precise time monitoring (i.e. scouting) and application of control tactics to the most susceptible stages of weed development. This can increase the effectiveness of chemical, mechanical and biological weed control methods. The present research evaluated critical periods for the potato crop in the Huambo highland region of Angola in different growing cropping seasons.

The results showed that the weed critical period for the potato crop in both the rainy and dry seasons is a long one, although it must be said that this matches the results of some other studies.

Further studies on soil fertility and potato crop growing techniques – e.g. on fertilizers and plant density (Oliveira, 2000), seed tuber quality, potato varieties that are adapted to these particular ecological conditions, soil coverage by organic mulches for the prevention of nutrient leaching, soil erosion, weed emergence and crop disease control (Döring et al., 2005), and irrigation methods – are required in order to develop recommendations that will help potato growers to reduce the large period of weed free and to improve yield.

In the present research, crop planting density was 6.25 tubers m^{-2}. This crop density was chosen to match the cropping system currently employed by growers. According to the results obtained by Lopes (1989), in early spring, in Portugal, with that potato planting density the crop ought to result in 100% soil coverage. The author achieved higher marketable potato yields as plant populations increased as a result of greater and earlier soil cover, as well as of a larger crop leaf area index/together with a larger crop leaf area index. In our studies, the tuber emergence can be considered poor, given that, on average, about 7,500 tubers per hectare failed to emerge. Considering the cost of potato seeds, this represents a considerable loss for growers. Nevertheless, based on the study by Lopes (1989), the proportion of emergent plants in our study ought to have given 100% soil coverage, but in fact the maximum soil cover was 85%. The reasons for this require study.

The results of the present study – namely the density and biomass of weeds over a long period – may indicate a constraint on plant development and a possible reduction in reproductive fitness with consequences for marketable potato yield. Weed emergence can be attributed to the effectiveness of the soil cover by the crop. During the two rainy growing seasons, the heavy precipitation – a normal occurrence – can cause soil particle disturbance; while during the dry season, the furrow irrigation has a similar effect. These combinations of factors may explain the constant emergence of seedlings (Booth et al., 2003) or the regrowth of *C. esculentus* tubers.

Given the negative impact of the perennial weed *C. esculentus* on potato yield, the use of selective herbicides in crop rotation should be considered, despite their low efficacy due to the fact that herbicide translocation is complicated, and dormant tubers (Ferrell & Vencill, 2004). The order of the crops in the sequence – e.g. maize before potato – determines the ability to use herbicides against this weed. Crop competition can also be used effectively against several weeds that affect potatoes (Boydston & Hang, 1995). The use of fast-growing crops, high planting densities and closely spaced rows all help with control. Some crops, such as small grains, out-compete with *C. esculentus* by forming dense canopies before it has a chance to establish itself.

However, given that organic farming is the current practice in the region, we suggest the use of organic mulches, since these reportedly control weeds and potato diseases (Litterick et al., 1999; Döring et al., 2005), and can also prevent nutrient leaching and soil erosion with the concomitant addition of organic matter.

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