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Integrating Economics in the Critical Period for Weed Control Concept in Corn

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The effect of weed interference on corn yield and the critical period for weed control (CPWC) were determined in Germany and Benin. Treatments with weed control starting at different crop growth stages and continuously kept weed-free until harvest represented the ''weed-infested interval.'' Treatments that were kept weed-free from sowing until different crop growth stages represented the ''weed-free interval.'' Michaelis–Menten, Gompertz, logistic and log–logistic models were employed to model the weed interference on yield. Cross-validation revealed that the log–logistic model fitted the weed-infested interval data equally well as the logistic and slightly better than the Gompertz model fitted the weed-free interval. For Benin, economic calculations considered yield revenue and cost increase due to mechanical weeding operations. Weeding once at the ten-leaf stage of corn resulted already profitable in three out of four cases. One additional weeding operation may optimize and assure profit. Economic calculations for Germany determined a CPWC starting earlier than the four-leaf stage, challenging the decade-long propagated CPWC for corn. Differences between Germany and Benin are probably due to the higher yields and high costs in Germany. This study provides a straightforward method to implement economic data in the determination of the CPWC for chemical and nonchemical weed control strategies.

Nomenclature: corn, *Zea mays* L.

Key words: Benin, corn–weed competition, Germany, Gompertz, logistic, mechanical weeding, Michaelis–Menten.

Corn has become the most important crop worldwide (FAOSTAT 2014; Shiferaw et al. 2011). Average yield levels of corn vary considerably between 0.3 t ha^{-1} (some African countries) and 9.8 t ha^{-1} (Italy and New Zealand), according to Oerke and Dehne (2004). In Central Europe, corn is mainly produced for fodder and industrial products (Shiferaw et al. 2011). Average corn yield in Southeastern Germany was 10.3 t ha^{-1} and was 11.0 t ha^{-1} in Southwestern Germany between 2008 and 2012 (Anonymous 2014a,b). These high yields can be achieved through very effective weed control, mainly done with herbicides in Western Europe (Seitz et al. 2006). In Benin (West Africa), corn is a main staple food crop (ONASA 2003; Shiferaw et al. 2011). Despite its alimentary and economic importance, corn yield is still very low, averaging 1.3 t ha^{-1} (FAOSTAT 2014, data 2008 to 2012). Vissoh et al. (2004) identified poor weed control as one of the main constraints because it is primarily done by hoeing.

The CPWC in corn is of high importance, owing to the crop's low competitiveness at early development stages. The CPWC was defined by Swanton and Weise (1991) as the crucial period that the field should be weed-free to prevent yield loss. Knezevic et al. (2002) provided suggestions on how to carry out field trials and data analyses to determine the CPWC. Field trials should have treatments with increasing length of weed competition, ''weed-infested interval,'' and with increasing length without weeds, ''weed-free interval.'' The former explains the early and continuous weed competition, whereas the latter emphasizes weed re-emergence at subsequent intervals.

The yield response to treatments is directly related to either the length or the lack of weed competition. Knezevic et al. (2002) recommended nonlinear regression employing the logistic model for the ''weed-infested interval'' and the Gompertz model for the ''weed-free interval.'' The intercepts of these two curves with an acceptable yield loss level (AYL) determine the CPWC. Hall et al. (1992) used 2% AYL to determine the CPWC in corn in Canada and found it began between three- and fourteen-leaf stage (leaf tip).

Koch and Kemmer (1980) found that the CPWC for corn in Germany started around the four- or six-

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leaf stage (fully developed collars) and ended at tassel emergence. They used LSD tests, assuming that weeds caused no yield loss if a treatment was not significantly different from the weed-free interval. This is a weak assumption for two reasons. Firstly, a yield difference of about 10 to 20% between treatments may not be identified (Oliver 1988). Secondly, LSD strongly depends upon data variability, and the structured character of the factor treatment "weed infestation" is not considered (Cousens 1988). Gantoli et al. (2013) determined the CPWC for corn in Benin in recent trials in a joint project with GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit). That project aimed to improve corn yield to a level of 2.5 t ha^{-1}, which corresponded to about 20% AYL from the weed-free plots. However, nonlinear regression converged only for data of one site. For the other site, multiple *t* tests were used without distinguishing between the weed-infested or weed-free intervals.

Parameterization of Gompertz and logistic models, as suggested by Hall et al. (1992), is disadvantageous, since no biological meaning can be assigned to all estimated parameters. Therefore, other commonly used equations with biologically meaningful parameters might be considered for CPWC calculation. Another disadvantage occurs when the AYL is determined without economic background. Dunan et al. (1995) used economically critical periods taking into account costs for PRE and POST chemical weed control in onions and yield gain due to control. Additionally, when hand weeding and hoeing have to be repeated over time to keep the crop weed-free as long as needed, these increasing costs must also be acknowledged. In developed countries, the standard concept of CPWC in corn omits these costs because commonly one herbicide application is done.

Considering that all trials in Koch and Kemmer (1980) date back nearly 40 yr, it is likely that cropping systems and corn hybrids have changed considerably since then. Also, the crop growth stage should be clearly specified. For instance, a determined "tip" leaf stage (i.e., as in Hall et al. 1992) might only be compared to a younger "fully developed collar" leaf stage (i.e., the BBCH-scale in Koch and Kemmer 1980). Thus, a reconsideration of the CPWC for Germany is warranted. The aims of this study were: (1) to use distinct data sets to compare different equations and their usability in this area of study; and (2) to determine the CPWC in corn for studies conducted in Germany and Benin, applying state of the art analyses and economic calculations that avoid arbitrarily chosen AYL.

Materials and Methods

Data sets from seven previously implemented trials in Germany and in Benin were used for analyses in this study. Further description of those experiments is given in Koch and Kemmer (1980), Keller et al. (2012), and Gantoli et al. (2013), and the most important characteristics are detailed in Table 1. In Germany, data of trials implemented by Koch and Kemmer (1980), here referred to as Koch–Kemmer1974, were used in the present study. Experiments in Koch–Kemmer1974 were carried out in Southwestern Germany (47° to 49°N, 7° to 10°E) and arranged in randomized complete block designs with four replicates, and the following treatments were applied: weed-infested until three- to four-leaf, weed-infested until five- to six-leaf, weed-infested until six- to seven-leaf, weed-infested until seven- to eight-leaf, weed-infested until eight- to nine-leaf, weed-infested until nine- to ten-leaf, weed-infested until eleven- to twelve-leaf, and whole season weed-infested. The weed-free interval treatments were: weed-free until three- to four-leaf, weed-free until five- to six-leaf, weed-free until six- to seven-leaf, weed-free until seven- to eight-leaf, weed-free until eight- to nine-leaf, weed-free until nine- to ten-leaf, and weed-free until eleven to twelve-leaf stage. No whole season weed-free treatment was included.

Data sets of recent trials implemented in 2009 and 2010 at the University of Hohenheim, research station Ihinger Hof (48°74′N, 8°93′E) were also used, here referred to as Ihinger-Hof 2009 and Ihinger-Hof 2010. The trials were installed as randomized complete block designs with four replicates. The applied treatments were: weed-free, weed-infested until four-leaf, weed-infested until eight-leaf, weed-infested until ten-leaf stage, and whole season weed-infested. Ihinger-Hof 2010 had an additional treatment weed-infested until flowering.

In Benin trials were implemented in 2010 and 2011, near Djougou (10°14′N, 1°23′E) and near Natitingou (10°19′N, 1°23′E), here referred to as Djougou 2010, Djougou 2011, Natitingou 2010, and Natitingou 2011. Experiments were arranged in randomized complete block designs with four replicates. Applied treatments included the aforementioned for the weed-infested interval in Ihinger-

Table 1. Details of the cultural practices and management, climate, and site characteristics of the data sets used in this study.

Variable	Koch–Kemmer	Ihinger-Hof	Djougou	Natitingou
Years	1974	2009–2010	2010–2011	
Climate	temperate		tropical	
T_{AVG}[a] (°C)	8.6[b]	8.8	26.8	
Precipitation[a] (mm)	1,019[b]	688	1,200	1,150
Soil type	—[c]	para-brown (luvisol)	ferruginous tropical	
Date of sowing	May 2[d]	April 21	June 10	June 22
		April 21	June 16	June 25
Sowing density (seeds ha^{-1})	—[c]	85,000	66,000	
Row spacing (m)	—[c]	0.75		
Seed spacing (m)	—[c]	0.16	0.40	
Tillage	—[c]	reduced tillage	ploughing	

[a] Annual average.

[b] Average of southwestern Germany in the respective year (Anonymous 2014e).

[c] Not given in Koch and Kemmer (1980).

[d] Estimate.

Hof, as well as treatments for the weed-free interval: weed-free until four-leaf, weed-free until eight-leaf, weed-free until ten-leaf, and weed-free until flowering stage.

The most abundant weeds were recorded for all trials. Variables assessed in the recent trials were corn and weed above-ground biomass at varying growth stages. Corn and weed biomass of the treatments with and without whole season weed-infestation were determined at the ten-leaf stage of corn, to allow comparison among sites regarding their productivity, weed community, and weed pressure.

The curves for the weed-infested and weed-free intervals were derived applying nonlinear regression to absolute yield data. For this, PROC NLMIXED in SAS (version 9.3, SAS Institute, Inc., Cary, NC; 2004) was used. A slightly modification of the logistic model in Hall et al. (1992) was fitted to data for the weed-infested interval (Equation 1; Knezevic et al. 2002):

$$Y = Y_{wf}\left\{\left[1/\left(e^{c(t-d)}+f\right)\right]+\left[(f-1)/f\right]\right\}+Block+r \qquad [1]$$

where Y is corn yield in t ha^{-1}, t is time in days after sowing (DAS), d is the inflection point, and c and f are constants. *Block* are the block-effects and r the residuals. In Koch–Kemmer 1974 block-effects could not be modelled because only mean values per treatment were available. The factor "100" cited in Knezevic et al. (2002) was replaced in Equation 1 with the average weed-free yield (Y_{wf}) of the corresponding data set.

The four-parameter log-logistic (Equation 2) and the three-parameter Michaelis–Menten (Equation 3) models were also fitted to the weed-infested interval data (Ritz and Streibig 2014):

$$\begin{aligned} Y &= C+\left[(D-C)/\left(1+e^{B[\ln(t)-\ln(E)]}\right)\right]+Block+r \qquad [2] \\ &= C+\left\{(D-C)/\left[1+(t/E)^{B}\right]\right\}+Block+r \end{aligned}$$

$$Y = D_2+\left[(C_2-D_2)/\left(1+E_2t^{-1}\right)\right]+Block+r \qquad [3]$$

where C and C_2 denotes the lower, and D the upper yield asymptotes, E and E_2 are time (t) in DAS at which weeds caused 50% of yield loss, and B is proportional to the slope around time E in Equation 2. D_2 is the yield for t approaching 0. The log–logistic model (Equation 2) is commonly used in dose-response studies and the Michaelis–Menten model (Equation 3) to derive yield loss caused by weeds (Cousens 1985; Ritz and Streibig, 2008, 2014). For the weed-infested interval, t is the time interval the crop experienced weed competition.

The Gompertz model was fitted to data for the weed-free interval (Equation 4; Knezevic et al. 2002):

$$Y = a\cdot e^{-be^{-kt}}+Block+r \qquad [4]$$

where a is the upper yield asymptote, and b and k are constants.

The log–logistic (Equation 2) and the Michaelis–Menten (Equation 3) models were also fit to data for the weed-free interval. C in Equation 1 denotes the yield for t approaching 0, and E is time (t) in DAS at which re-emergence of weeds causes 50% yield loss for the weed-free interval. Parameters in Equation 3 were renamed to derive Equation 5:

$$Y = C_3+\left[(D_3-C_3)/\left(1+E_3t^{-1}\right)\right]+Block+r \qquad [5]$$

where C_3 denotes the yield for t approaching 0, and D_3 the upper yield asymptote. E_3 is time (t) in DAS at which re-emergence of weeds causes 50% yield

Table 2. Costs of corn production for farmers in Benin and Southern Germany.

	Production costs (EUR ha^{-1})	
Input	Benin	Germany
Seed	5	180
Fertilizer	107	395
Field operations	160[a]	497[b]
Plant protection products		115
Drying		475[c]
Stocking	15	96
Further costs[d]	—	165[e]
Total	287	1,923

[a] Benin: ploughing, sowing, earthing up, fertilizing, harvesting, cleaning of the cobs, including one weeding operation, each additional weeding operation costs 15 EUR ha^{-1}; field operations are carried out manually.

[b] Germany: ploughing, sowing, fertilizing, spraying, harvesting, transport of produce; field operations are carried out by a contractor.

[c] Dependent on produce harvested; a yield of 10.3 t ha^{-1} (average yield of the Southern region from 2008–2012, according to Anonymous 2014a) was taken for calculation by the cost calculator, assuming a water content of 31.5% at harvest and a water content of 14% after drying.

[d] Assumption: land belongs to the farmer.

[e] Insurance, book keeping, etc.

loss. Parameters C_2 or C_3 were dropped from Equations 3 or 5, respectively, when the lower yield asymptote estimation was ≤ 0. For the weed-free interval, t is the time interval the crop was without weed competition. To compare among models, cross-validation "leave one out" was employed (Hastie et al. 2009).

Threshold Values for CPWC. For Koch–Kemmer 1974, a total AYL of 2% was employed to determine the length of the critical period according to Knezevic et al. (2002). The value of the lower weed-free asymptote was chosen as weed-free yield. For the other German data sets, a different approach was taken. All costs for seeds, fertilizer, plant protection products, machines, and labor correspond to the minimum threshold that needed to be covered to avoid economic losses. These costs were around 1,923 Euros (EUR) ha^{-1} (e.g., South German farm), corresponding to a minimum yield of 10.3 t ha^{-1} (Table 2). An average corn price from 2008 to 2012 of 187 EUR t^{-1} was used (Anonymous 2014a,c). At the intersection of the "weed-infested interval" with this minimum threshold, all costs are covered but no profit is yet achieved. Profit starts if weed competition is removed when yield in the weed-infested interval is above 10.3 t ha^{-1}.

The CPWC was calculated in Benin in five steps. First, the length of the weeding period was determined for each yield level as the difference between the weed-free and weed-infested intervals. Second, the achievable yield associated with the determined weeding periods was calculated as follows: Yield losses caused by weeds allowed to grow until the first weeding operation and yield losses caused by re-emerging weeds after the last weeding operation were subtracted from the estimated weed-free yield (upper yield asymptote). The modelled yield was restricted to not drop below the lower yield asymptote of the weed-free and weed-infested intervals. Yield curves could be created based on these calculations ($yield_{[weeding\ period]}$, in t ha^{-1}). Third, the revenue dependent on the weeding period ($revenue_{[weeding\ period]}$, in EUR ha^{-1}) was calculated by multiplying the yield curve with the farm gate crop price.

Costs for inputs and management operations were gathered from the Beninese agricultural extension service (Table 2); the farm gate crop price was 229 EUR t^{-1}. Costs for inputs and labor, which include all management activities plus one weeding operation, were 287 EUR ha^{-1}, and further costs were 15 EUR ha^{-1} for every additional weeding operation. In the fourth step, those costs were used to derive the "cost function" for every additional weeding operation. Weeding intervals of 2 wk were taken into account and assumed as continuous intervals. The cost function corresponds to a linear function for which "fixed" costs are the intercept and additional weeding costs are the slope. Finally, the difference between revenue and cost functions described the "profit function" ($profit_{[weeding\ period]}$, in EUR ha^{-1}). The maximum value of this function determined the length of the crop should be kept weed-free to maximize profit. Curves and intersection points were approximated using linear interpolation in R (R Core Team 2013).

Results and Discussion

Weed species found in Germany and Benin were typical for the regions where the experiments were conducted (Mehrtens et al. 2005; Terry 1983; Vissoh et al. 2004). In Ihinger-Hof, annual broadleaved weeds were dominant. Common lambsquarters (*Chenopodium album* L.), catchweed bedstraw (*Galium aparine* L.), and blackgrass (*Alopecurus myosuroides* Huds.) occurred in 2009, while common chickweed [*Stellaria media* (L.) Vill.], shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.],

Table 3. Average aboveground biomass of corn in the continuously weed-free and whole season weed-infested interval and average weed biomass in the weed-infested interval at ten-leaf stage of the crop; standard deviation in parentheses.

		Corn biomass		Weed biomass
Site	Year	Weed-free	Weed-infested	Weed-infested
		kg m^{-2}		
Ihinger Hof	2009	0.64 (0.11)	0.34 (0.10)	—[a]
	2010	0.41 (0.05)	0.07 (0.01)	0.38 (0.20)
Djougou	2010	0.25 (0.13)	0.18 (0.07)	0.09 (0.02)
	2011	0.11 (0.04)	0.07 (0.04)	0.35 (0.16)
Natitingou	2010	0.12 (0.05)	0.21 (0.15)	0.04 (0.01)
	2011	0.08 (0.02)	0.06 (0.01)	0.01 (0.01)

[a] No data available.

and catchweed bedstraw were more abundant in 2010. Koch and Kemmer (1980) characterized the weed pressure as medium, including the species barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes], and common lambsquarters. In Benin, annual and perennial grasses and broad-leaved weeds were of importance. At Djougou, yellow foxtail, beard of the lion [*Bulbostylis hispidula* (Vahl) R. W. Haines], and hairy signalgrass [*Urochloa villosa* (Lam.) T.Q. Nguyen] were identified in 2010, while beard of the lion, Asian spikesedge (*Kyllinga squamulata* Thonn. ex Vahl), and seedbox [*Ludwigia hyssopifolia* (G. Don) Excel] were abundant during 2011. At Natitingou, light-blue snakeweed [*Stachytarpheta jamaicensis* (L.) Vahl), tropical girdlepot [*Mitracarpus hirsutus* (L.) DC], and flat-top mille graines [*Oldenlandia herbacea* (L.) Roxb] were the most abundant during 2010, while tropical girdlepot, Jamaica vervain, and Piedmont flatsedge (*Cyperus distans* L.F.) were most seen in 2011.

Despite the absence of weed competition, corn biomass in the weed-free plots varied highly among sites and years (Table 3). Without weed competition, average corn biomass in Benin was between 15 and 47% lower than that in Ihinger Hof (Germany) at ten-leaf stage. Weed biomass accounted for 84% at Ihinger-Hof 2010, 34% at Djougou 2010, 83% at Djougou 2011, 14% at Natitingou 2010, and 18% at Natitingou 2011 of total plant biomass. These data highlight the variability in corn-weed competition, which depends on weed composition, crop status, and environmental conditions.

Nonlinear Regression. Applied models converged for all data sets except Natitingou 2010 (Tables 4 and 5). Cross-validation revealed that Equation 2 fitted data, as well as Equation 1 for the weed-infested interval both with an average correlation coefficient of 0.71. Equation 2 fitted data for the weed-free interval slightly better than Equation 4, especially for Natitingou 2010 as no convergence was reached either for the full or the sub data sets during cross validation (Table 6). For the weed-free interval, parameter E (Equation 2) was 427 DAS for Djougou 2010 and 117 DAS for Natitingou 2011, which were longer than the whole growing season of corn, and therefore no upper yield asymptote could be reached. Contrarily, parameter estimates for Equation 2 for the other data sets were biologically sound; i.e., *C* and *D* corresponded to the yields obtained under continuously weed-infested and weed-free conditions. Parameter *E* (Equation 2) was generally higher for the German weed-infested intervals compared with those from Benin, indicating that the point at which weeds caused 50% of yield loss was reached later. A reason for this can be ascribed to the different climate conditions that influenced plant growth (crop and weeds). For further experimentation, the log–logistic model could be considered in addition to the often used Gompertz (Equation 4) and logistic models (Equation 1) as parameterized by Hall et al. (1992) and methodologically described and modified by Knezevic et al. (2002).

Critical Period for Weed Control. The log–logistic model (Equation 2) was employed for economic calculations and determination of the CPWC. For Koch–Kemmer 1974, the CPWC started around the six- to seven-leaf stage and ended between the eight- and nine-leaf stage (Figure 1). For Ihinger-Hof 2009, the onset of the CPWC was before the four-leaf stage (Figure 2A). In contrast for Ihinger-Hof 2010, the yield level was below the cost threshold. Even without weed competition over the whole season, costs for corn production could not be covered that year with the reported price (Figure 2B).

The CPWC determined for corn in Germany in the 1970s, which is between four- and six-leaf stage

Table 4. Parameter estimates of the weed-infested interval using the logistic model (Equation 1) as in Knezevic et al. (2002) and the log–logistic model (Equation 2) and the Michaelis–Menten model (Equation 3); standard errors in parentheses.

		Logistic (Equation 1)[a]			Log–logistic (Equation 2)[b]				Michaelis–Menten (Equation 3)[c]		
Site	Year	c	d	f	C	D	B	E	D_2	C_2	E_2
Koch–Kemmer	1974	0.12 (0.05)	65 (16)	2.26 (1.62)	1.21 (9.73)	5.51 (0.09)	6.17 (3.84)	83 (50)	6.82 (0.54)	0 (0)	146 (47)
Ihinger Hof	2009	0.07 (0.04)	55 (11)	2.08 (0.38)	5.27 (0.98)	10.44 (0.76)	4.15 (2.57)	64 (13)	10.72 (0.78)	0 (0)	183 (55)
	2010	0.05 (0.02)	62 (5)	1.18 (0.07)	1.04 (0.58)	8.47 (0.42)	3.73 (1.36)	66 (5)	8.58 (0.52)	0 (0)	52 (9)
Djougou	2010	0.09 (0.04)	15 (6)	1.82 (0.21)	1.03 (1.06)	3.40 (0.25)	1.14 (0.97)	26 (23)	3.41 (0.24)	0.87 (0.53)	29 (18)
	2011	0.27 (0.27)	40 (7)	1.53 (0.14)	0.97 (0.16)	2.80 (0.10)	11.15 (8.42)	41 (5)	3.16 (0.23)	0 (0)	67 (17)
Natitingou	2010	0.40 (1.17)	10 (13)	2.54 (0.19)	1.92 (0.17)	3.32 (0.19)	2.10 (1.90)	10 (4)	3.35 (0.19)	1.79 (0.21)	7 (6)
	2011	2.34 (64.58)	35 (8)	2.05 (0.22)	1.43 (0.14)	2.98 (0.11)	83.24 (6553.70)	35 (6)	3.11 (0.22)	0 (0)	97 (28)

[a] d inflection point, c and f constants.

[b] C lower asymptote (t ha^{-1}), D upper asymptote (t ha^{-1}), E time in days after sowing at which weeds caused 50% yield loss, B is proportional to the slope around time E.

[c] C_2 lower asymptote (t ha^{-1}), D_2 (t ha^{-1}) yield for t (time) approaching 0, E_2 time in days after sowing at which weeds caused 50% yield loss.

Table 5. Parameter estimates of the weed-free interval using the Gompertz model (Equation 4) as in Knezevic et al. 2002 and the log–logistic model (Equation 2) and the Michaelis–Menten model (Equation 5); standard errors in parentheses.

		Gompertz (Equation 4)[a]			Log–logistic (Equation 2)[b]				Michaelis–Menten (Equation 5)[c]		
Site	Year	a	b	k	C	D	B	E	C_3	D_3	E_3
Koch–Kemmer	1974	6.21 (0.33)	1.47 (0.16)	0.04 (0.01)	1.55 (0.16)	5.78 (0.17)	−3.78 (0.69)	28 (1)	1.48 (0.29)	9.47 (1.73)	60 (26)
Djougou	2010	3.59 (0.52)	0.86 (0.15)	0.02 (0.01)	1.42 (0.25)	8.46 (14.26)	−0.70 (0.39)	427 (1960)	1.46 (0.22)	4.70 (1.35)	77 (66)
	2011	2.75 (0.16)	1.26 (0.23)	0.06 (0.01)	0.98 (0.16)	2.58 (0.10)	−6.09 (3.05)	21 (4)	0.84 (0.19)	3.57 (0.48)	36 (16)
Natitingou	2010	nc[d]	nc	nc	2.03 (0.12)	8.60 (208.78)	−13.18 (74.51)	117 (378)	1.64 (0.12)	$2.9\ 10^{7}$ (0.00)	$1.9\ 10^{8}$ (0.00)
	2011	3.05 (0.21)	0.94 (0.23)	0.06 (0.02)	1.34 (0.27)	2.95 (0.19)	−5.10 (3.92)	18 (4)	1.25 (0.29)	3.45 (0.43)	19 (12)

[a] a upper yield asymptote (t ha^{-1}), b and k are constants.

[b] C yield for t approaching 0 (t ha^{-1}), D upper asymptote (t ha^{-1}), E time in days after sowing at which re-emergence of weeds causes 50% yield loss, B is proportional to the slope around time E.

[c] C_3 yield for t (time) approaching 0, D_3 upper asymptote (t ha^{-1}), E_3 time in days after sowing at which re-emergence of weeds causes 50% yield loss.

[d] Abbreviation: nc, no convergence reached.

Table 6. Correlation coefficients of the cross-validation (leaving one out) for the different models.

		Weed-infested interval			Weed-free interval		
Site	Year	Logistic (Equation 1)	Log–logistic (Equation 2)	Michaelis–Menten (Equation 3)	Gompertz (Equation 4)	Log–logistic (Equation 2)	Michaelis–Menten (Equation 5)
Koch-Kemmer	1974	0.76	0.78	0.62	0.95	0.93	0.75
Ihinger Hof	2009	0.34	0.37	0.50	—[a]	—	—
	2010	0.88	0.86	0.86	—	—	—
Djougou	2010	0.63	0.61	0.64	0.52	0.62	0.61
	2011	0.87	0.86	0.63	0.77	0.84	0.75
Natitingou	2010	0.68	0.67	0.68	nc[b]	0.64	0.61
	2011	0.80	0.79	0.61	0.63	0.63	0.58

[a] no data available.

[b] Abbreviation: nc, no convergence reached.

and tassel emergence (Koch and Kemmer 1980), provided reason to use a total AYL of 2% in the present study. In Koch–Kemmer 1974, weeds caused only a significant yield loss if allowed to grow until nine- to ten-leaf stage (weed-infested interval). For the weed-free interval, weeds caused only a significant yield reduction if they re-emerged and were able to compete with the crop immediately after the three- to four-leaf stage. The LSD varied between 1.02 and 1.11 t ha^{-1}. Such reductions in yield are not acceptable for farmers and represent more the detection limit of the methodology than the lack of a yield effect (Cousens 1988). Using nonlinear regression on the Koch–Kemmer 1974 data set in this study with a total AYL of 2%, the CPWC started earlier compared with the LSD analyses. However, an arbitrary AYL hardly ensures validity of the CPWC. Using recent data sets and current costs and prices, the CPWC in Germany starts before the four-leaf stage, especially if some profit is to be achieved. During years of unfavorable growing conditions (e.g., as experienced in Ihinger-Hof 2010), costs cannot be covered, and farmers face difficult economic situations. However, these circumstances are mitigated through direct payments German farmers receive if they fulfill certain standards in the field of environment, animal welfare and health,

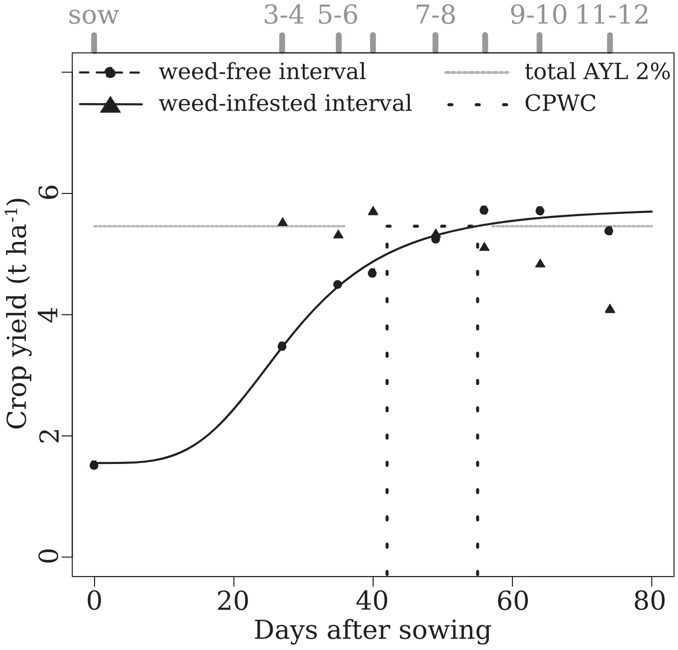

Figure 1. Critical period for weed control (CPWC) for Koch–Kemmer 1974 data set, using the log–logistic model (Equation 2) on the weed-infested interval. A total acceptable yield loss of 2% was chosen. Growth stages: Sow, sowing; 3-4-L, three- to four-leaf stage, etc.

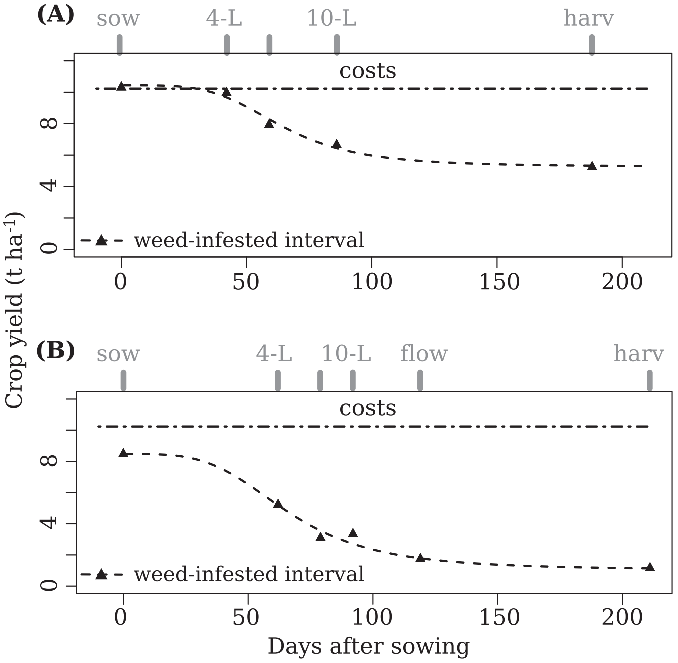

Figure 2. Weed-infested interval using the log–logistic model (Equation 2) on Ihinger-Hof 2009 data set (A) and on Ihinger-Hof 2010 (B). Production costs under German conditions correspond to a threshold of about 10.3 t ha^{-1}. Growth stages: Sow, sowing; 4-L, four-leaf stage; 10-L, ten-leaf stage; flow, flowering; harv, harvest.

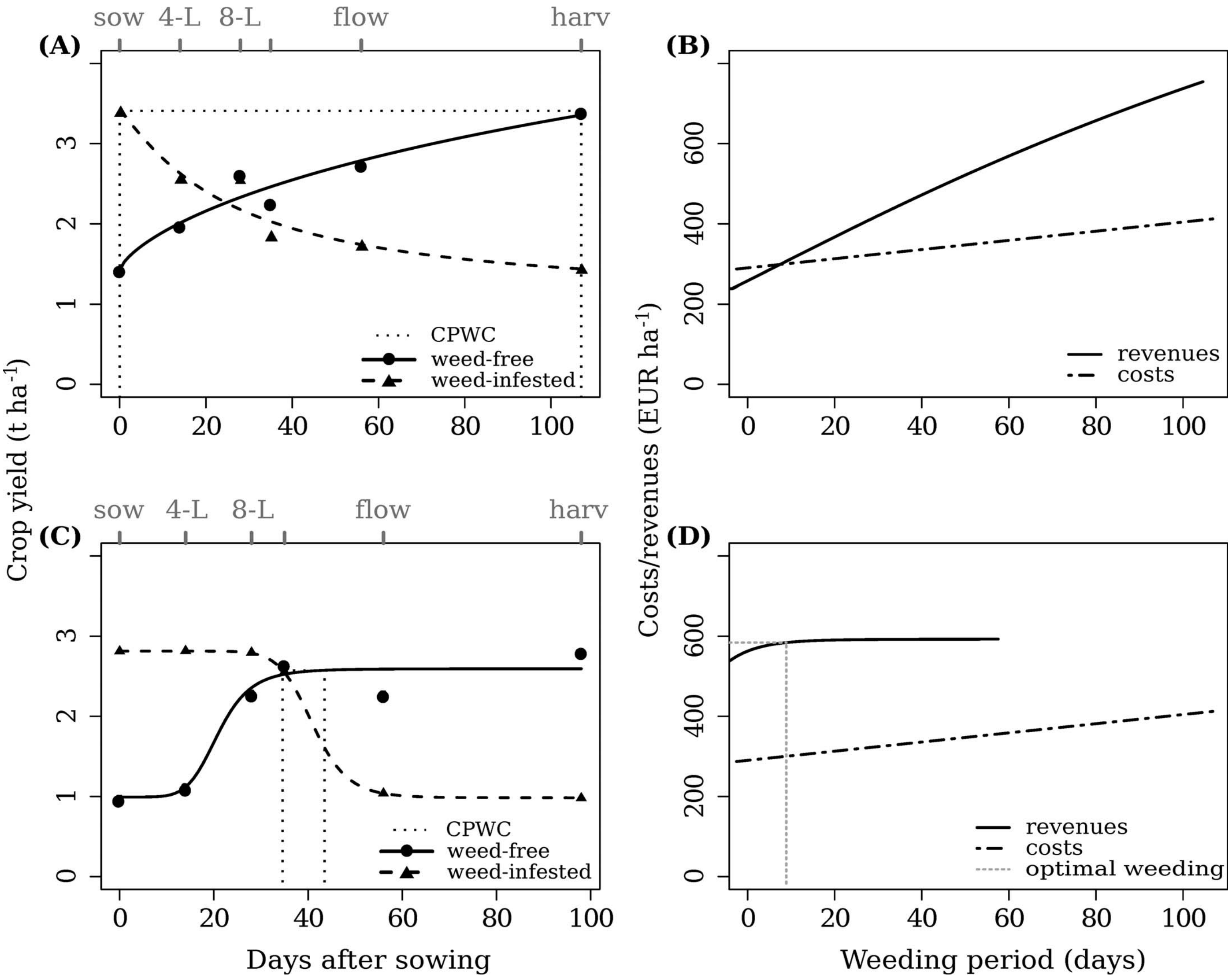

Figure 3. Determined weed-infested and weed-free intervals using the log–logistic model (Equation 2) for Djougou 2010 (A) and Djougou 2011 (C), and critical period for weed control (CPWC); development of revenue and costs depended on the time the crop was kept weed-free for Djougou 2010 (B) and Djougou 2011 (D). Growth stages: Sow, sowing; 4-L, four-leaf stage; 8-L, eight-leaf stage; flow, flowering; harv, harvest.

plant health, food safety, and if they keep the land in good environmental and agricultural condition (Cross-compliance) (Anonymous 2014d).

The onset of the CPWC is of major relevance for German farmers. In contrast, the end of the application window for herbicides must be before the six-leaf stage of the crop to avoid phytotoxicity (Baer et al. 2010). A herbicide with residual activity can be added to the tank mixture to ensure weed suppression until corn plants fully shade the soil. Still, late emerging weeds might cause additional losses, which are not considered in the current approach. Thus, gross profit margin could be even lower. Dunan et al. (1995) applied costs and benefit functions for PRE and POST chemical weed control in onions. Contrarily, production costs were considered crucial in the present study because the yield obtained due to weed control should cover most of those costs, if not all of them.

Weed competition resulted in a yield loss between 50 and 85% for the whole season weed-infested interval in Germany (Figure 2). Although the timing of weed control could be optimized, it seems that there is little potential to increase yield. For both Ihinger-Hof 2009 and Ihinger-Hof 2010, yield of the weed-free interval plots corresponded to the country's average grain yield; i.e., 2009: 9.75 t ha^{-1}, and 2010: 8.79 t ha^{-1} (FAOSTAT 2014). Yield in Ihinger-Hof 2010 was lower than that in 2009, and the effect of weed competition was much more pronounced due to cold weather early in the season. Yield was 88 and

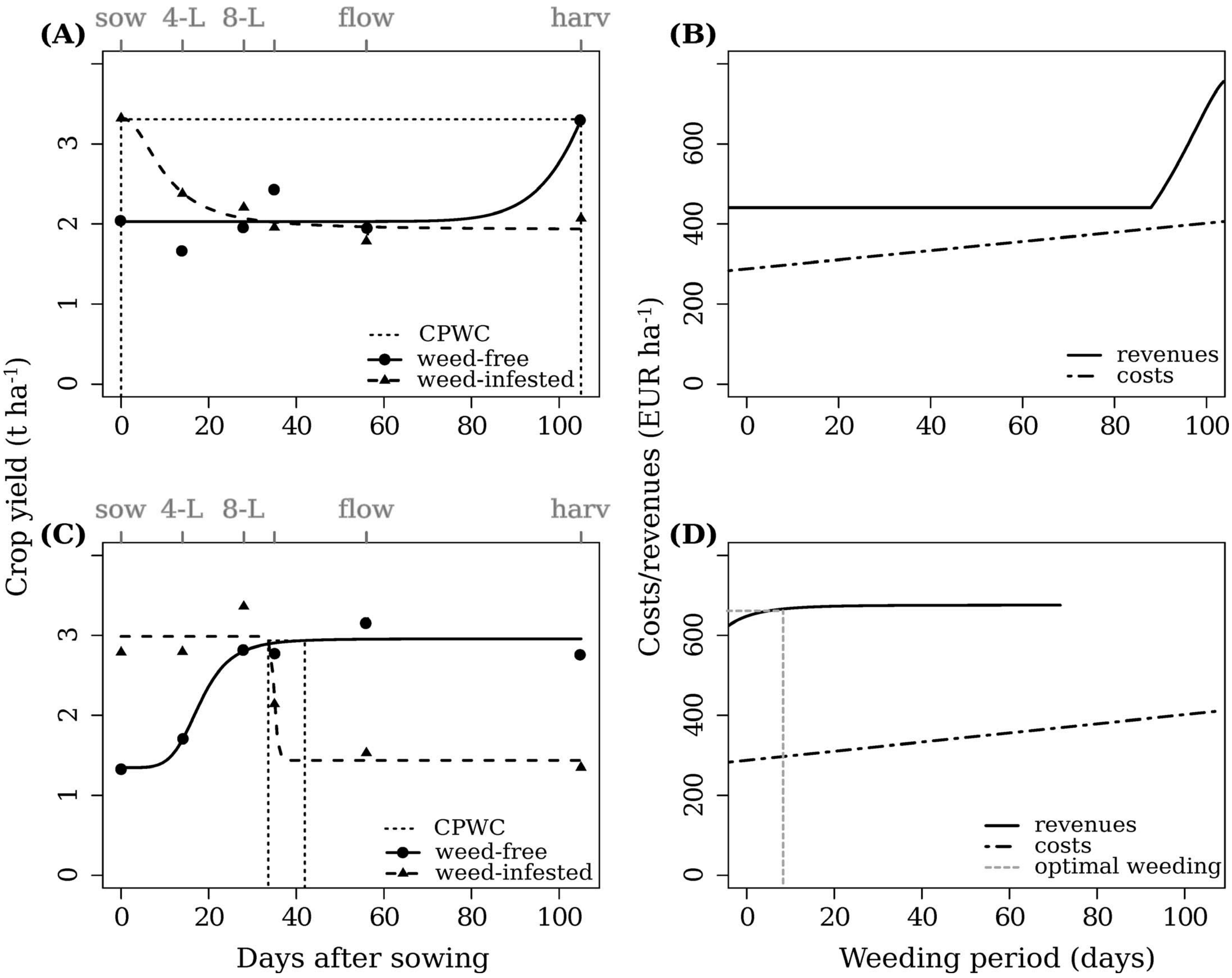

Figure 4. Determined weed-infested and weed-free intervals using the log–logistic model (Equation 2) for Natitingou 2010 (A) and Natitingou 2011 (C), and critical period for weed control (CPWC); development of revenue and costs depended on the time the crop was kept weed-free for Natitingou 2010 (B) and Natitingou 2011 (D). Growth stages: Sow, sowing; 4-L, four-leaf stage; 8-L, eight-leaf stage; flow, flowering; harv, harvest.

52% higher in Ihinger-Hof 2009 and 2010, respectively, compared with the yield in Koch–Kemmer 1974. This increase can be ascribed to the breeding progress and improved crop management (Duvick 1997).

Liu et al. (2009) reported that corn plants detect weeds via the photoreceptor phytochrome at very early growth stages, through measurements of a reduced R/IR-ratio around corn plants in the presence of weeds. They found that corn increased shoot/root ratio to overgrow the weeds, which might cause lodging and drought stress at later growth stages. Page et al. (2009) indicated that this phenomenon could also affect the concept of the CPWC, and suggested to farmers to control weeds early, since weed occurrence triggers shade avoidance response. Economic calculations in the present study emphasize that herbicides should be applied at earlier crop development stages than the CPWC in Germany, as determined by Koch and Kemmer (1980).

In Benin, yield in the whole season weed-free interval was much higher than the average grain yield achieved in this region (1.3 t ha^{-1}), but still low compared with high input systems. Weed competition throughout the whole season reduced yield between 36 and 64%. These trials clearly demonstrated the potential to increase yield by reducing weed competition. Weeding once resulted in a profit (revenues minus costs) of about 152 to 354 EUR ha^{-1} in three out of four cases and in a loss of 32 EUR ha^{-1} in one case (Figures 3 and 4; B and D). For Djougou 2011 and Natitingou 2011, a very short economically optimal weeding period of about 8 d was determined at the ten-leaf stage (Figures 3 and 4; C and D). For Djougou 2010 and Natitingou 2010, continuous weeding during the whole season would have maximized profit (Figures 3 and 4; A and B), owing to the relatively low labor costs. A fast turnover of weeds may explain the observed low biomass, nevertheless weeds showed a highly detrimental effect on yield at Natitingou. Whether continuous weeding would be economically justified depends on the opportunity costs of labor and farmers' needs (Vissoh et al. 2004).

Gantoli et al. (2013) used an AYL of about 20% (nearly 0.5 t ha^{-1} reduction from the weed-free plots), and identified a longer CPWC. In the present study, the CPWC in Benin differed as a result of the alternative threshold approach and models used. However, many other factors that affect the crop status could have influenced the CPWC. In Benin, corn biomass was considerably higher in 2010 than 2011. Vernon and Parker (1983) also found high variability between sites in length of CPWC in corn in Zambia, due to differences in soil moisture, nutrients, and weed infestation. The late onset of the CPWC in Benin can also be explained by the farming practice of putting two seeds per hole, resulting in intrarow spacing of 0.40 m. This apparent wider intrarow spacing could provide an advantage to the crop competition against weeds. However, the two corn plants will be affected by intraspecific competition.

Weed control needed to start much earlier in the high input systems in Germany to ensure at least coverage of costs compared with the low input systems in Benin (compare Figures 2A and 2B with 3C and 3D and 4C and 4D) based on the CPWC determined in this research. Under German economic and temperate climate conditions (i.e., high costs and greater weed than corn growth rates early in the season), chemical weed control is mandatory and important to avert the risk of a financial loss.

Corn yields could be increased by well-timed weed control. In Germany, farmers should apply herbicides early POST or even PRE, provided that weather and crop allow it, to avoid economically unacceptable yield loss caused by early emerging weeds. This study modifies the CPWC determined some decades ago for Germany. In Benin, one to two well-timed weeding measures could increase profit considerably and weeding should be done around the ten-leaf stage of the crop. Using biologically meaningful parameters for modelling yield data increases understanding of the relationship between length and onset of weed competition. Thresholds based on economic calculations improve the validity and relevance of the CPWC for farmers. We provide a simple approach to implement these calculations into the methodology used for the determination of the CPWC.

Acknowledgments

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Erratum

Keller, M, G Gantoli, J Möhring, C Gutjahr, R Gerhards, and V Rueda-Ayala (2014) Integrating economics in the critical period for weed control concept in corn. Weed Sci 62:608–618

Equations 1, 2, 3, and 5 were misprinted. The corrected equations are below:

$$Y = Y_{wf}\left\{\left[1/\left(e^{c(t-d)}+f\right)\right]+[(f-1)/f]\right\}+Block+r \quad [1]$$

$$Y = C+\left[(D-C)/\left(1+e^{B[\ln(t)-\ln(E)]}\right)\right]+Block+r = C+\left\{(D-C)/\left[1+(t/E)^{B}\right]\right\}+Block+r \quad [2]$$

$$Y = D_2+\left[(C_2-D_2)/\left(1+E_2t^{-1}\right)\right]+Block+r \quad [3]$$

$$Y = C_3+\left[(D_3-C_3)/\left(1+E_3t^{-1}\right)\right]+Block+r \quad [5]$$

The equations are correct in the online version of the article, located at http://www.wssajournals.org/doi/pdf/10.1614/WS-D-13-00184.1.

We apologize for this error.