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Sugar Beet Yield Loss Predicted by Relative Weed Cover, Weed Biomass and Weed Density

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Abstract

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Sugar beet yield loss was predicted from early observations of weed density, relative weed cover, and weed biomass using non-linear regression models. Six field experiments were conducted in Germany and in the Russian Federation in 2012, 2013 and 2014. Average weed densities varied from 20 to 131 with typical weed species compositions for sugar beet fields at both locations. Sugar beet yielded higher in Germany and relative yield losses were lower than in Russia. Data of weed density, relative weed cover, weed biomass and relative yield loss fitted well to the non-linear regression models. Competitive weed species such as *Chenopodium album* and *Amaranthus retroflexus* caused more than 80% yield loss. Relative weed cover regression models provided more accurate predictions of sugar beet yield losses than weed biomass and weed density.

Keywords: crop-weed interaction; weed competition; yield loss function

Weed management plays an important role in sugar beet production. Wide row spacing and slow development in early growth stages result in late canopy closure. Up to 100% of the crop yield may be lost because of weed competition if weed control is poor or is not performed at all (Kropff & Spitters 1991). Effective weed control is needed mainly during the critical period of sugar beet development, which is approximately the period during the first 60 days after emergence. Then, sugar beet does not tolerate co-existence with weeds without losing yield (May & Wilson 2006; Jalali & Salehi 2013). Weeds need to be removed until the 8-leaf stage of sugar beet. Emerging weeds after the 8-leaf stage did not cause any significant sugar beet yield losses (Jursík *et al.* 2008). In European sugar beet production, *Chenopodium album* L., *Amaranthus retroflexus* L., *Galium aparine* L., *Matricaria chamomilla* L., *M. inodora* L., *Stellaria media* (L.) Vill., and *Polygonum convolvulus* L. are the most abundant weed species (Petersen 2008).

Multiple (3–4) applications of selective herbicides are the common practice in European sugar beet weed control programs. Herbicides are sprayed after every weed emergence wave to keep the crop weed-free. Alternatively, post-emergent inter-row hoeing in combination with herbicide band applications within the row have successfully been practiced to control weeds in sugar beet (Kunz *et al.* 2015).

Precise estimations of sugar beet yield loss due to weed competition are needed for decisions on integrated weed management strategies. Usually, empirical models are used to estimate the crop yield loss by weed competition from early observations of weed density (Cousens 1985) and relative weed cover (Kropff & Spitters 1991; Lotz *et al.* 1996). Models fitted better for relative weed cover than for weed density (Ali *et al.* 2013), because relative weed cover accounts for the size of the crop and weeds and relative time of emergence (Cousens *et al.* 1987). However, tall and upright growing weed species such as *Echninochloa crus-galli* L. and *C. album* were still

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underestimated in their competitive effect on crops when relative weed cover was measured. Therefore, Milberg and Hallgren (2004) suggested relating weed biomass to crop yield loss. Still, the problem remains comparing competitive effects of mixed weed populations. Berti and Zanin (1994) used a density equivalent to determine the competitive effects of each weed species.

Estimated crop yield losses may vary considerably between different sugar beet production areas and years due to different climatic conditions, soil types, weed populations, productivity, and cropping practices. Results of the relation between sugar beet yield loss and weed competition have so far been derived from field studies in Western Europe (Kropff & Spitters 1991; Lotz *et al*. 1996) and in the USA (Nichterlein *et al*. 2013). However, sugar beet yields and summer precipitation have been reported to be lower in the sugar beet production area in the Russian Federation on Chernozem soils than in Western Europe and in the USA (Vislobokova & Ivanova 2013). Therefore, predicted yield losses may vary between the experimental sites in Germany and in the Russian Federation.

The objective of this study was to predict sugar beet yield losses from early observations of weed density, relative weed cover and weed biomass using non-linear regression models. The following hypotheses have been tested:

– Early assessments of weed biomass result in more accurate predictions of sugar beet yield loss than those of weed density and relative weed cover.
– Relative yield losses of sugar beet are higher in the Russian experiments than at the German site due to weed competition and the competitive ability of weed species.

MATERIAL AND METHODS

Experimental sites. Six field studies were conducted in typical sugar beet growing areas of Germany and the Russian Federation. Three field experiments were conducted at the experimental station of the University of Hohenheim – Ihinger Hof (IHO), Baden Württemberg, Germany (48°74'03''N, 8°91'56''E) in 2012, 2013 and 2014. The soil at IHO is classified as Haplic Luvisol, the soil type is a silty clay loam with high fertility and good water retention capacity.

Three experiments were carried out in the Russian Federation, two in 2013 and one in 2014 at an experimental station located at Doktorovo (DOK) in the Lipetsk region (52°78'47''N, 39°02'72''E). The soil at the Russian locations is a typical Voronic Chernozem with high content of organic matter and high biological activity.

Environmental conditions and cropping practices. The climate at IHO is temperate cool with average yearly temperatures of 9.2°C in 2012, 8.7°C in 2013, and 10.4°C in 2014. The cumulative annual precipitation was favourable for sugar beet growth with 727 mm in 2012, 923 mm in 2013, and 763 mm in 2014 except for two short periods of drought in spring in 2012 and 2014. The sites in the Russian Federation at DOC are characterised by a temperate continental climate with average yearly temperatures of 7.0°C in 2013 and 6.6°C in 2014 and annual precipitation totals of 462 mm in 2013 and 340 mm in 2014. All three summer periods were hot and dry.

Experimental design. The trials were arranged as completely randomized block design with four replications. All experimental plots were 8 m long and 3 m wide with a row distance of 0.5 m. Sugar beets were sown at a density of 110 000 seeds/ha after strip tillage in April (IHO) and early May (DOK). The previous crop was winter wheat at all locations. The experimental design includes four treatments. Treatment 1 is an untreated control. Treatment 2 was kept weed-free by continuous hand-weeding. In treatment 3 and 4, weed infestation was manipulated to achieve a wide range of infestation levels over the experiment. This facilitates modelling the relationship between weed competition and yield loss. At IHO, a relatively low weed pressure of approximately 20–40 weeds/m^2 was expected in the untreated control plots. Therefore, 400 and 800 seeds/m^2 of *C. album* were sown in treatments 3 and 4 to increase weed density by approximately 50 and 100%. At DOK, a higher natural weed infestation of 100–150 weeds/m^2 was expected. Therefore, 35 and 70% of the emerged plants of *C. album* and *A. retroflexus* were removed by hand in treatments 3 and 4 to establish targeted weed densities.

Data collection and analysis. The number of emerged sugar beets (*n*/ha) was counted at the BBCH 12 (Hess *et al*. 1997) development stage of the crop and averaged over all plots in all experiments. All weed infestation measurements were carried out at the BBCH 18 growth stage of the crop. Weed density per species was counted within a 1 m^2 frame in the centre of each plot. Relative weed cover was calculated by digital image analysis. RGB images of

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1 m^2 were taken in the sampling areas where weeds were counted before. The images were processed with the computer program ImageJ Version 1.47a. Green colour of weeds and sugar beet was separated from soil using the Colour Threshold procedure. To distinguish between crop and weed, an interactive graphic editing program was utilised to eliminate the leaf area of weeds and only to display the crop leaf area. Crop and weed biomass was also measured in the same sampling area where weeds were counted before. Entire crop and weed plants were dug out, washed and underground and aboveground plant parts were collected separately and dried in a hot-air oven at 80°C for 72 h until the weight was constant. Dry weight was recorded. In autumn, sugar beets were harvested manually in an area of 2.5 m^2 per plot. Fresh mass of sugar beets was recorded. For the analysis of extractable sugar content, beets were washed and processed to measure their sugar content. At DOK, a portable refractometer was used to determine the %Brix value of the sugar juice and at IHO, the laboratory polarimetric method was applied. Both methods correspond to the ICUMSA standards (ICUMSA 2013) and provided equal results.

Statistical analysis. The relation of weed density and weed biomass to the relative yield loss of sugar beet was estimated by fitting both parameters into the non-linear regression model proposed by Cousens (1985):

$$Y_L = \frac{q \times d}{1 + q \times d/a} \tag{1}$$

where: Y_L – relative yield loss; d – weed density or weed biomass; q – yield loss per unit of weed parameter; a – maximum yield loss

The effect of weed cover on the relative yield loss of sugar beet was estimated by fitting the same two parameters into a non-linear regression model proposed by Kropff and Spitters (1991):

$$Y_L = \frac{q \times L_W}{1 + \left[\left(\frac{q}{a}\right) - 1\right] \times L_W} \tag{2}$$

where: Y_L – relative yield loss; L_W – relative weed cover; q – yield loss per unit of weed parameter; a – maximum incurred yield loss

The relative yield loss was calculated using the following function:

$$Y_L = \frac{Y_{wf} - Y_w}{Y_{wf}} \tag{3}$$

where: Y_L – relative yield loss; Y_{wf} – weed-free yield; Y_w – yield in weedy plots

The relative weed cover was calculated according to the equation:

$$L_W = \frac{L_{\text{weed}}}{L_{\text{weed}} + L_{\text{crop}}} \tag{4}$$

where: L_W – relative weed cover; L_{weed} – weed cover; L_{crop} – crop cover

The fit to the model was tested by plotting normal QQ plots and residuals distribution plots. For modelling weed-crop interaction, the statistical program R, Version 2.15.0 (2015) was used.

RESULTS

Crop and weed densities, crop yields. In all experiments, the sugar beet emerged, established and normally developed further (Table 1).

Weed densities were higher at DOK with a total density of 58–131 weeds/m^2 than at IHO with 20–86 weeds/m^2 (Table 2). The composition of weed infestations was also different in both regions. Warm-season weeds *A. retroflexus* and *E. crus-galli* occurred only in the Russian Federation. *S. media*, *C. album*, and *M. inodora* dominated at IHO (Table 2). Weed compositions were representative of sugar beet production areas at both locations.

On average, yields were roughly 45% lower at the Russian site than at IHO in all treatments, likely caused by low precipitation and shorter growing season there (Table 3).

Modelling weed-crop interactions. All datasets show a positive correlation between weed density and sugar beet yield loss. Even low weed densities already caused significant yield reductions. At DOK 2013, 2014 and IHO 2013, 50% of the maximum weed density caused about 80% yield reduction. Weed competition and maximum yield losses on average

Table 1. The number of emerged sugar beets (number/ha) in all experiments

	DOK 1 2013	DOK 2 2013	DOK 2014	IHO 2012	IHO 2013	IHO 2014
Crop density	102 800	104 400	97 200	90 000	100 000	107 200

IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

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Table 2. Density (number/m^2) of the most abundant weed species in all experiments measured at the BBCH 18 growth stage of the crop (Hess *et al.* 1997) in untreated control plots using a 1 m^2 frame in the centre of each plot

Weed species	DOK 1 2013	DOK 2 2013	DOK 2014	IHO 2012	IHO 2013	IHO 2014
Amaranthus retroflexus	21.2	43.7	4.0	–	–	–
Chenopodium album	39.1	2.8	28.9	5.8	27.6	7.5
Cirsium arvense	–	–	0.4	–	–	–
Echinochloa crus-galli	1.4	1.3	1.3	–	–	–
Fumaria officinalis	4.2	2.0	–	–	–	–
Galium aparine	–	–	0.2	–	–	–
Galeopsis tetrahit	8.8	1.5	0.4	–	–	–
Lamium purpureum	7.8	2.7	18.6	–	1.5	–
Matricaria inodora	1.0	–	–	1	43.1	13.7
Poa annua	–	–	–	–	3	–
Polygonum aviculare	–	1.5	2.2	–	–	–
Polygonum convolvulus	17.1	2.3	46.2	8.2	3	–
Polygonum lapathifolium	3.3	–	9.2	–	–	–
Setaria glauca	1.0	–	–	–	–	–
Sonchus arvensis	–	–	–	3.0	2.5	–
Stellaria media	–	–	–	–	5.2	–
Thlaspi arvense	1.9	–	1.2	–	–	–
Veronica persica	–	–	–	0.7	–	4.9
Viola arvensis	–	–	18.5	1.0	–	–
Total weed density	106.8	57.8	131.1	19.7	85.9	26.1

IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

were higher at DOK than at IHO. The weed density model shows a satisfactory fit to the data with regression coefficients ranging from 0.95 to 0.98 (Figure 1).

Relative weed cover data were distributed less homogeneously than weed densities (Figure 2). Hence, at DOK and IHO most values of relative weed cover ranged between 0.5 and 1 and similar as for weed density, only very few data were in the range of the economic weed threshold. At DOK 2 2013, the most abundant weed species was *A. retroflexus* L. regardless of the high variation in weed density (from 25 to 110 plants/m^2), relative weed cover ranged from 0.75 to 1. A similar situation was observed at DOK 1 2013, where *Chenopodium album* L. was the most abundant species. Relative weed cover regression graphs look less steep compared to the lines for weed density. Therefore, the weed cover model predicted a lower yield reduction at lower relative weed cover, which is not in line with the weed density analysis.

As it was expected, the relative yield loss of sugar beet was correlated positively with weed biomass. However, the estimated yield loss was less accurate than for relative weed cover. The site with the highest density of *A. retroflexus* showed a 95% sugar beet yield reduction caused by only 10 g/m^2 of weed biomass at BBCH 18, which was 1.8% of the maximum weed biomass (Figure 3). The graphs of weed biomass and weed cover models look very similar. Like the relative weed cover – sugar beet yield regression model, the weed biomass model predicted the lowest relative yield loss for IHO 2014. This complies with the output of the weed cover model.

Table 3. Average sugar beet yield (t/ha) and white sugar yield (t/ha) of the weed-free control at all experimental locations

	DOK 1 2013	DOK 2 2013	DOK 2014	IHO 2012	IHO 2013	IHO 2014
Sugar beet yield	45.2	54.6	37.9	83.3	82.9	95.0
White sugar yield	7.2	10.2	8.6	15.0	12.8	16.8

IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

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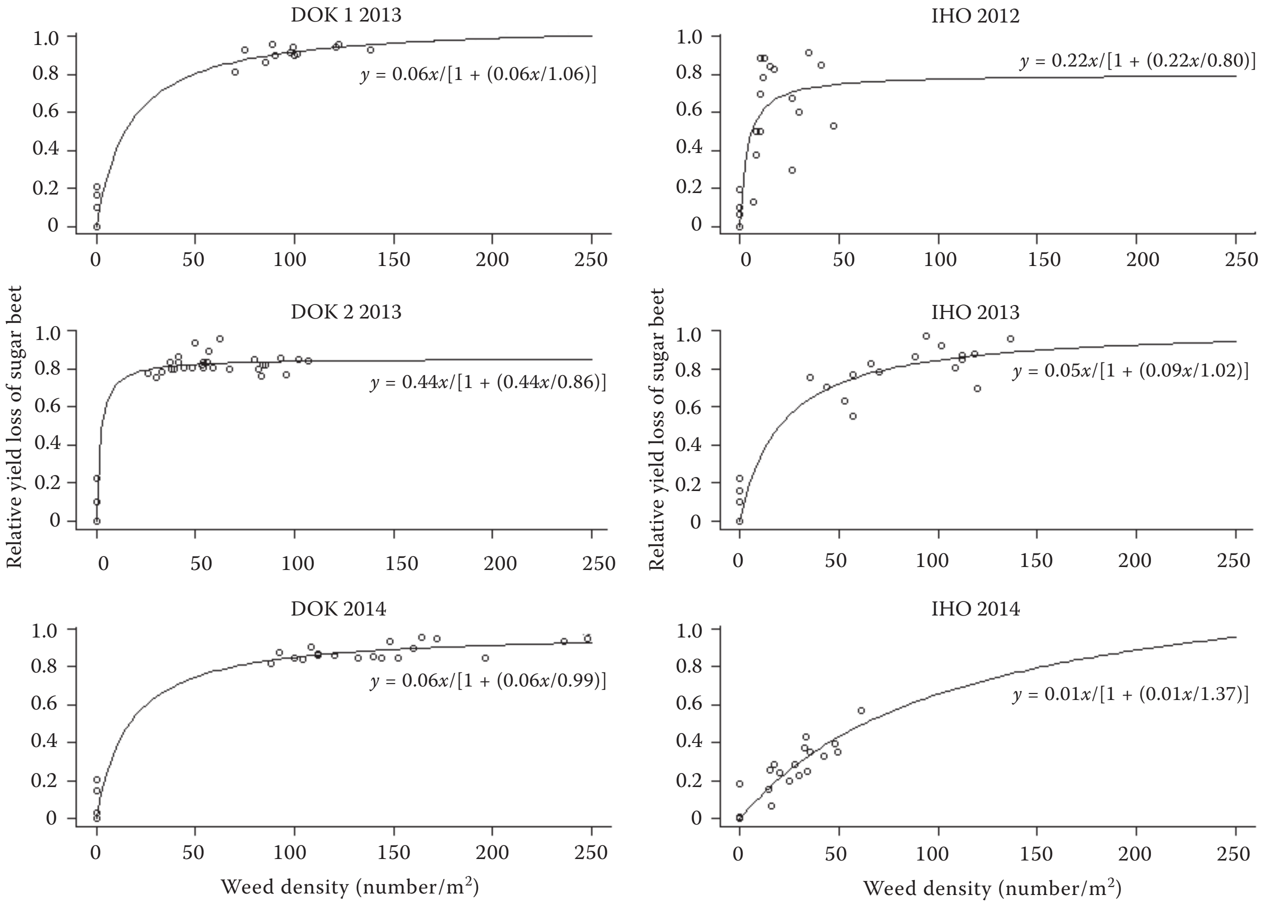

Figure 1. Relation of the relative yield loss of sugar beet to weed density in all experimental locations and years

IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

Relative weed cover provided the best estimator of sugar beet yield loss, followed by weed biomass and weed density (Table 4). The weed density regression model showed no strong correlation between relative damage coefficient and relative yield loss and the standard errors for *q* and *a* in the data set were higher than for relative weed cover and weed biomass.

Table 4. Regression parameters calculated for the two-parameter model of relative (A) sugar beet yield loss–weed density interaction modified according to Cousens (1985), (B) sugar beet yield loss-relative weed cover interaction according to Kropff and Spitters (1991), and (C) sugar beet yield loss-weed biomass interaction modified according to Cousens (1985)

Environment	A		B		C	
	q ± SE	*a* ± SE	*q* ± SE	*a* ± SE	*q* ± SE	*a* ± SE
DOK 1 2013	0.06 ± 0.06	1.07 ± 0.17	1.78 ± 1.38	0.97 ± 0.05	0.08 ± 0.12	0.96 ± 0.09
DOK 2 2013	0.44 ± 0.48	0.86 ± 0.04	11.01 ± 16.89	0.83 ± 0.02	1.41 ± 1.77	0.83 ± 0.01
DOK 2014	0.06 ± 0.03	0.99 ± 0.07	10.76 ± 7.11	0.90 ± 0.02	0.09 ± 0.06	0.95 ± 0.05
IHO 2012	0.22 ± 0.17	0.80 ± 0.15	1.77 ± 1.44	0.72 ± 0.08	0.01 ± 0.01	0.77 ± 0.18
IHO 2013	0.05 ± 0.02	1.02 ± 0.12	1.01 ± 0.34	0.93 ± 0.05	0.01 ± 0.001	1.15 ± 0.21
IHO 2014	0.01 ± 0.003	1.37 ± 0.95	0.13 ± 0.03	0.43 ± 0.03	0.01 ± 0.001	0.58 ± 0.07

q – competitive ability of the weeds ± standard error (SE); *a* – maximum yield loss ± SE; IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

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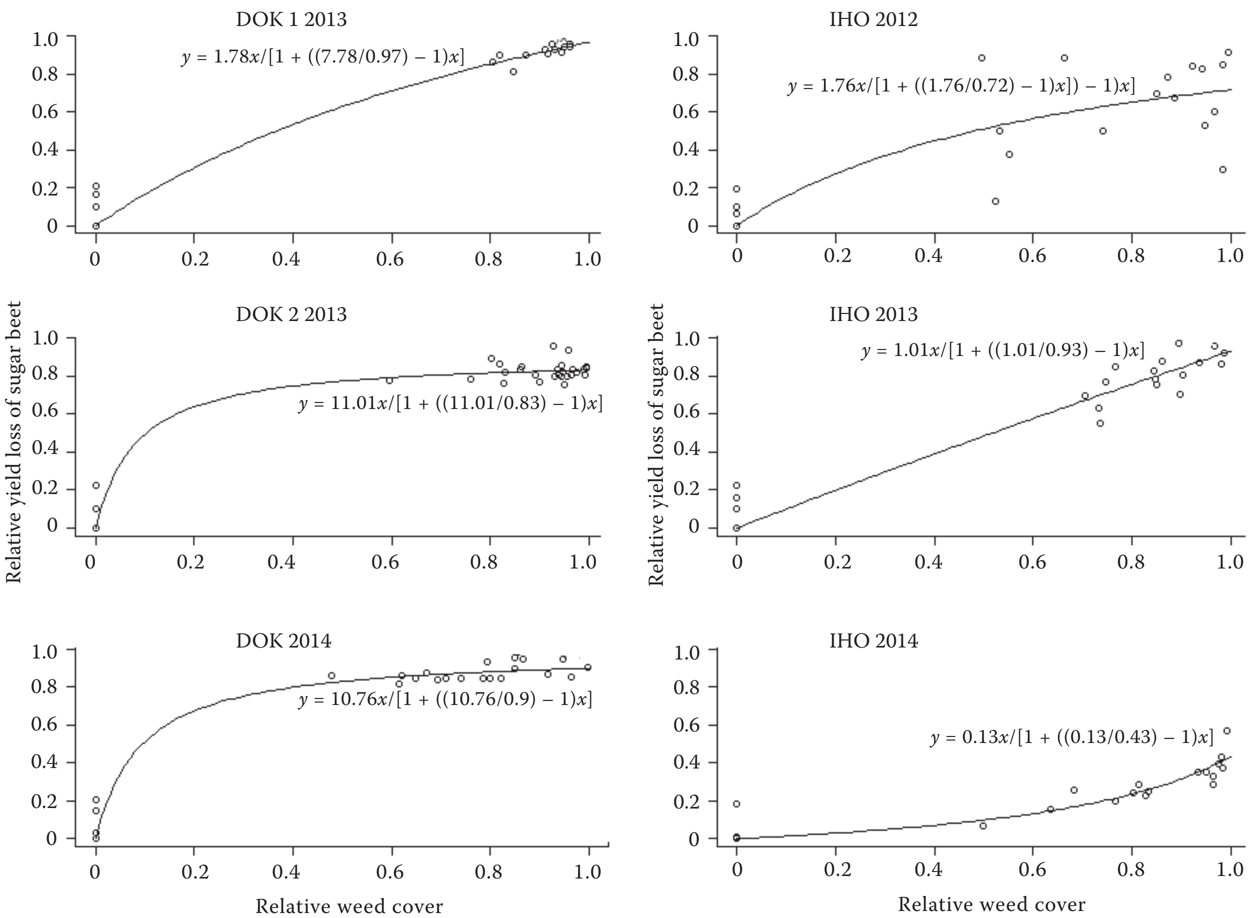

Figure 2. Relation of the relative yield loss of sugar beet to relative weed cover in all experimental locations and years

IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

DISCUSSION

Over all seasons, *A. retroflexus* and *E. crus-galli* were among the most abundant weed species at the DOK trial site, located in the central Chernozem region of the Russian Federation. Continental climate at DOK characterised by hot summers and water shortage gives a competitive advantage to C-4 plants over C-3 plants (Ziska & Runion 2007). Cool-season weed species such as *S. media* and *M. inodora* were abundant only at IHO, located in southwestern Germany in an area with the more maritime type of climate. Therefore, the results of the study confirm the hypothesis that warm and dry growing conditions in the Russian Federation favour more warm-season weed species than in the temperate region of Germany.

One reason for the higher weed infestation in the experiments at the Russian site than at IHO in Germany are large soil weed seed banks, which are yearly replenished by the seeds dropping from uncontrolled weeds (Kapustin 2012). A second reason for higher weed infestations at DOK in the Russian Federation is the high soil organic matter content, which strongly reduces the availability of soil active herbicides in the soil water (May & Wilson 2006) due to adsorption and enhanced breakdown. A third reason could be the lower competitive ability of the crop due to water deficiency.

The hypothesis that the relative yield loss due to weed competition and the competitive ability of weed species are higher under Russian growing conditions than in Germany is confirmed. The regression estimates of weed cover and weed biomass gave higher maximum yield losses and relative damage coefficients for the Russian site than for the German experiments. At DOK, the relative weed cover model estimate of q parameter ranged between 1.8 and 11.0. At IHO, q-values ranged only from 0.1 to 1.8. The highest value of q was calculated for DOK 2 in 2013 and 2014, where *A. retroflexus*, *C. album*, and *P. convolvulus* were the most abundant weed species. This corresponds with

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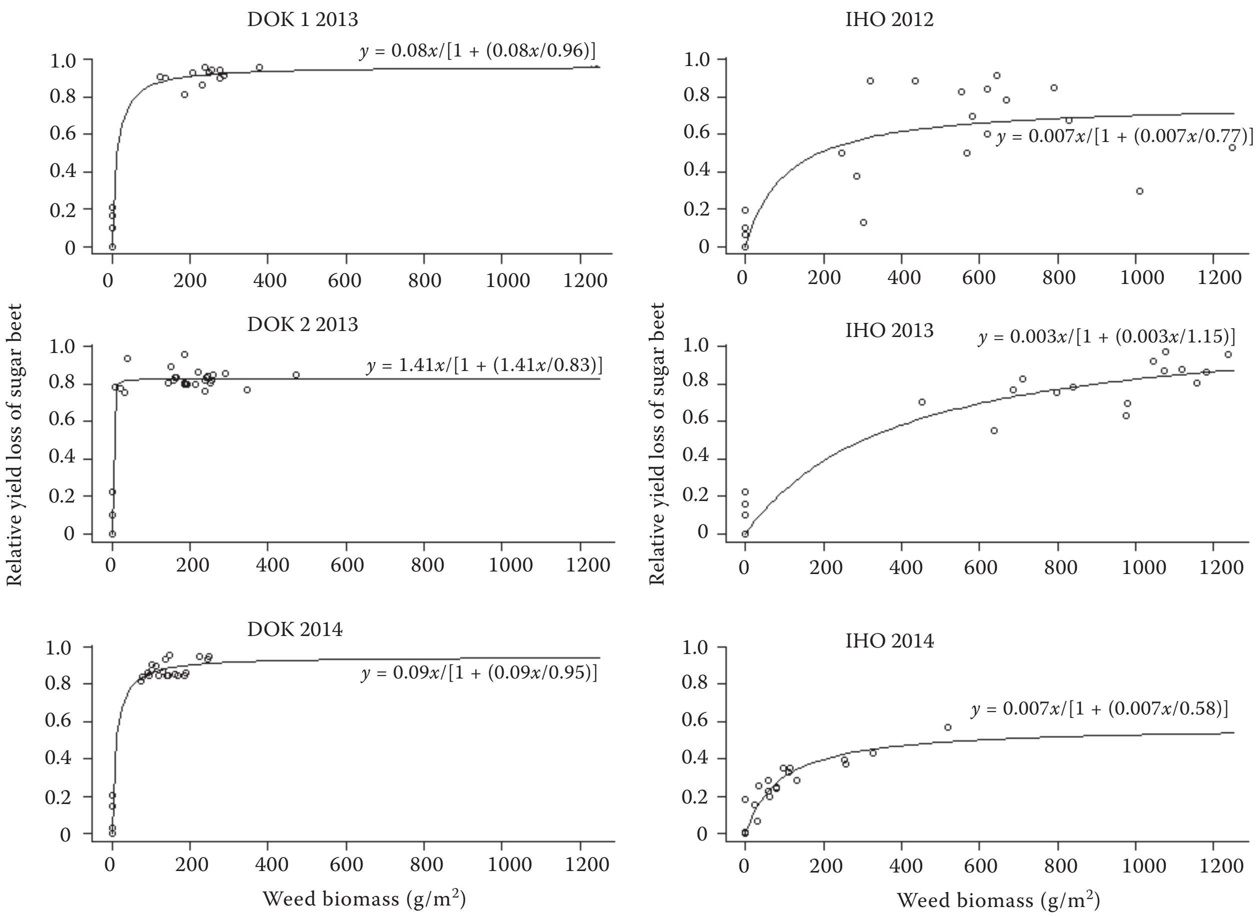

Figure 3. Relation of the relative yield loss of sugar beet to weed biomass in all experimental locations and years

IHO – Ihinger Hof, Germany; DOK – Lipetsk region, Russia

the statement that these species are among the most serious competitors of sugar beets (Petersen 2008; Jalali & Salehi 2013). Serious yield reductions were recorded when these species escaped control (Petersen 2008; Gummert *et al.* 2012; Jalali & Salehi 2013). The steep regression line at low infestation levels at DOK could also be a result of severe drought. At DOK 2014, annual precipitation was about 240 mm, which is less than 50% of the long-term average precipitation in this region (Hydrometcentre of Russia 2015). Lotz *et al.* (1996) also found a strong influence of climatic conditions on the crop-weed interaction.

The use of weed biomass in forecast tools of crop yield loss is very complicated. It requires destructive sampling and further processing of collected material, which needs time and equipment. In comparison, scouting for weed density is more feasible. The measurement of weed cover gave the most accurate prediction of the sugar beet yield loss in our study. Weed cover seems to be the most suitable parameter for decision algorithms for weed management in sugar beets.

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