Eike-Hennig Vasel, Erwin Ladewig, Bernward Märländer

Weed composition and herbicide use strategies in sugar beet cultivation in Germany

Unkrautzusammensetzung und Herbizidstrategien im Zuckerrübenanbau in Deutschland

Abstract

Weed composition and herbicide use in sugar beet fields varied in the last decades. This study was conducted to determine and analyse changes in weed composition and herbicide use strategies on regional and national scale in Germany based on data of the Sugar Beet Cultivation-survey (1994–2010) and NEPTUN-survey – Sugar Beet (2005, 2007 and 2009). On national scale, the occurrence of the most important common weeds has partly tripled and difficult-to-control weeds partly doubled from 1996 to 2010. Most important common weeds were goosefoot (CHESS), knotweed (POLSS) and cleaver (GALAP) with a spread of at least 36% up to 79%. The most difficult-to-control weeds were knotweed (POLSS), annual mercury (MERAN) and fool's parsley (AETCY), which occurred on less than 26% of the acreage in 2010. Acreage of mulch tillage systems and post-emergence treatments increased, while treatment frequency was relatively constant at approximately 3.0–3.5. Number of herbicide products and active ingredients used per treatment were relatively constant at 2.5 and 4.0, respectively, but treatment index per treatment changed significantly between the years from 2.0 to 2.4. Exemplarily, fields of exemplary regions in the north, west and south were characterised by specific weed compositions, which were regulated by adopted herbicide use strategies. Strategies differed in treatment frequency, varying from 2.9 to 4.5, number of herbicide products per treatment, varying from 2.2 to 3.5, number of active ingredients per treatment, varying from 3.6 to 4.8 and treatment index, varying from 1.47 to 2.51 in 2009. For the first time, the analysis of weed composition was done in relation to herbicide use strategies by comparable data. Weed species-specific adoption of treatment patterns, herbicide use intensity and reduced application rates clarify the implementation of the Integrated Pest Management in sugar beet cultivation, which is part of the EU-Directive 2009/128/EG for a sustainable use of pesticides.

Key words: Herbicides, active ingredients, treatment index, difficult-to-control weeds, NEPTUN-survey, Sugar Beet Cultivation-survey, Integrated Pest Management, National Action Plan

Zusammenfassung

Das Unkrautauftreten und der Herbizideinsatz in Zuckerrüben haben sich in den letzten Dekaden sehr verändert. Dieser Artikel bezieht sich auf die Bestimmung und die Analyse von Entwicklungen im Unkrautauftreten sowie deren Regulierung durch Herbizidstrategien auf regionaler und nationaler Ebene. Hierfür wurden Daten aus der Umfrage Produktionstechnik im Zuckerrübenanbau (1994–2010) und der NEPTUN-Erhebung Zuckerrüben (2005, 2007 und 2009) verwendet. Im Zeitraum von 1996 bis 2010 hat sich der Anteil von häufig auftretenden Unkräutern nahezu verdreifacht, und von schwer zu bekämpfenden Unkräutern verdoppelt. Die wichtigsten häufig auftretenden Unkräuter waren Gänsefußgewächse (CHESS), Knötericharten (POLSS) und Klettenlabkraut (GALAP) mit einem Vorkommen auf 36% bis 79% der Fläche. Die häufigsten schwer zu bekämpfenden Unkräuter waren Knötericharten (POLSS), Bingelkraut (MERAN) und Hundspetersilie (AETCY), welche 2010 auf weniger als 26% der

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Fläche vorkamen. Während der Flächenanteil von Mulchsaat und Nachauflaufbehandlungen stetig ansteigt, liegt die Behandlungshäufigkeit relativ konstant bei etwa 3–3,5. Auch die Anzahl eingesetzter Herbizide und Wirkstoffe je Behandlung liegt relativ konstant bei 2,5 bzw. 4, jedoch änderte sich der Behandlungsindex signifikant von 2 auf 2,4. Anhand von Beispielregionen im Norden, Westen und Süden wurde die spezifische Verunkrautung einer Region erfasst, und mit der jeweilig angepassten Herbizidstrategie verglichen. Die Strategien unterschieden sich im Jahr 2009 hauptsächlich in der Behandlungshäufigkeit, die zwischen 2,9 und 4,5 variierte, der Anzahl an eingesetzten Herbiziden je Behandlung, die zwischen 2,2 und 3,5 variierte, der Anzahl eingesetzter Wirkstoffe je Behandlung, die zwischen 3,6 und 4,8 variierte und dem Behandlungsindex, der zwischen 1,47 und 2,51 variierte. Zum ersten Mal wurde dadurch eine Verunkrautung mit einer entsprechenden Herbizidstrategie in Bezug gesetzt. Die unkrautartspezifische Anpassung der Behandlungsmuster, die Herbizidintensität und die Reduktion von Aufwandmengen verdeutlichen die Verinnerlichung des integrierten Pflanzenschutzes im Zuckerrübenanbau, welcher Bestandteil der EU-Direktive 2009/128/EG für eine nachhaltige Verwendung von Pestiziden ist.

Stichwörter: Herbizide, Wirkstoffe, Behandlungsindex, schwer-bekämpfbare Unkräuter, NEPTUN-Erhebung, Umfrage Produktionstechnik im Zuckerrübenanbau, integrierter Pflanzenschutz, Nationaler Aktionsplan

1 Introduction

Since the beginning of sugar beet cultivation in the early 19th century weed control was laborious; in the row it was combined with hand singling of approximately 1 mio plants ha^{-1} to final densities of about 70,000 plants ha^{-1}. Between rows weed control was conducted by hand or machine hoe. At this time, difficult-to-control weeds were barnyard grass (ECHCG), couch grass (ELYME), canada thistle (CIRAR) and field bindweed (CONAR) (KOLBE, 1985). Hand singling and weeding became more expensive, since progressing industrialisation bound workers and wage level increased. Thus, profitable sugar beet cultivation became more and more challenging in the 1950s. In the 1960s the development of sufficient selective herbicide active ingredients (a.i.) and monogerm seed in connection with single-seed drills decreased manual labour need extremely (HANF et al., 1976).

Pyrazon (Chloridazon) was approved (2*4,000 g a.i. ha^{-1}) pre/post-emergence in the 1960s as the first common selective herbicide a.i. However, efficacy against e.g. knotweeds (POLSS) was low. Phenmedipham was approved (960 g a.i. ha^{-1}) post emergence in the 1970s and showed a high efficacy, but monocots and late emerging weeds got more widespread. Metamitron was approved (7,000 g a.i. ha^{-1}) pre-emergence in the late 1970s and applied in tank mixtures with phenmedipham post-emergence (7,000 g a.i. ha^{-1}) which led to a higher efficacy. Annual mercury (MERAN) got a regional and cleaver (GALAP) a wider spread. Ethofumesate was approved (2,000 g a.i. ha^{-1}) post emergence in 1985 and again had an increased efficacy when used in tank mixtures with metamitron, phenmedipham and an oil additive. First it was used in a single and later split in 2 to 4 treatments. Metolachlor was approved (1,500 g a.i ha^{-1}) pre-emergence, cycloxydim (500 g a.i. ha^{-1}) and fluazifop-butyl (750 g a.i. ha^{-1}) post-emergence in the 1990s with a high efficacy in controlling monocots. Trifulsulfuron was approved (43.7 g a.i. ha^{-1}) post-emergence and quinmerac (250 g a.i. ha^{-1}) pre/post-emergence in the mid 1990s and had a high efficacy against „new weeds“ e.g. fool‘s parsley (AETCY) and three-cleft bur-marigold (BIDTR) occurring on regional scale (AMMON, 2002). Since then, no new herbicide a.i. has been authorised in sugar beet cultivation in Germany.

Today's low dosage active ingredients composition applied as tank mixtures require information about the field- and region-specific weed population. However, reliable data on the weed composition and the more and more sophisticated herbicide use in practical weed control have not yet been published. Simultaneously, public awareness has increased in the last decades and public is more and more critical about pesticide use, although authorisation is legally regulated.

The intensity of pesticide use is characterised by treatment index and treatment frequency. For that, data about pesticide use on field scale are required as surveyed by NEPTUN-surveys beginning in 2000 (ROSSBERG et al., 2002). The first German action plan aiming to reduce pesticide use was the Plant Protection Product Reduction Programme (Reduktionsprogramm chemischer Pflanzenschutz) in 2004 (BMVEL, 2004) which included data of NEPTUN-survey. The National Action Plan on Sustainable Use of Plant Protection Products (Nationaler Aktionsplan zur nachhaltigen Anwendung von Pflanzenschutzmitteln) followed in 2008 (BMELV, 2008) in order to increase transparency and documentation of pesticide use as well as focusing on the necessary minimum of pesticide applications. The EU-Directive 2009/128/EG for a sustainable use of pesticides (ANONYMOUS, 2009a) demands from all EU-member countries to set up action plans till December 2012. Thus, data about pesticide use on farm scale have to be collected, analysed and interpreted for scientific purposes and policy advice which has not been done until now.

The objective of this study was to analyse (i) the species-specific compositions of weed populations in German sugar beet cultivation, and (ii) the different herbicide use strategies on regional scale. In addition, the principal aim was to create a perspective for public acceptance of future chemical weed control in sugar beet.

Two different basic approaches were approved being representative for sugar beet cultivation in Germany: 1. 'Sugar Beet Cultivation-survey 1994–2010' including key figures of pesticide use and weed control for 22 sugar beet factory catchment areas (BUHRE et al., 2011), 2. 'NEPTUN-survey 2005, 2007 and 2009' with data of pesticide use from approximately 1,000 fields p.a. (Rossberg et al., 2010).

2 Material and Methods

Data collection

The Sugar Beet Cultivation-survey (SBCS) was coordinated by the Institute of Sugar Beet Research, Göttingen (IfZ). It was carried out beginning in 1994 and consists of a biannual main-survey and an annual intermediate-survey which covers Germany's total sugar beet acreage (Merkes et al., 1996; Merkes et al., 2001). The main-survey includes information on preceding crop, sowing, soil tillage, plant protection and harvest. The intermediate-survey contains parameters which are influenced by annual variation such as sowing date, seed dressing and appearance of pests and diseases. Data were estimated by local sugar factory advisers together with advisers from growers associations and official advisory services. Some aspects could be specified very precisely e.g. harvesting and transporting technique. In 2010, analysis of data was based on a regional scale in relation to 22 sugar factory catchment areas (Buhre et al., 2011). Out of these, five geographic regions (north, northeast, east, south and west) were assigned. Data was weighted by sugar beet acreage.

The **NEPTUN-survey** (**N**etzwerk zur **E**rmittlung der **P**flanzenschu**t**zmittelanwendung in **u**nterschiedlichen, landwirtschaftlich relevanten **N**aturräumen Deutschlands) was established and organised by the Julius Kühn-Institut (JKI former Biologische Bundesanstalt für Land- und Forstwirtschaft) in 2000 to provide data on pesticide use, and thus, to increase the transparency of its use in Germany (Rossberg, 2006). The NEPTUN-surveys sugar beet were carried out in 2005, 2007 and 2009 in cooperation with the IfZ (Rossberg, 2006; Rossberg et al., 2008; Rossberg et al., 2010). The NEPTUN-survey 2009 contained 15 regions called ERA (**E**rhebungs**r**egionen **A**ckerbau) in which pesticide use was surveyed from at least 30 farms per ERA (Rossberg et al., 2010). The parameters treatment time, pesticide product, application rate and treated area were recorded. More detailed information is given in the NEPTUN-reports (Rossberg, 2006; Rossberg et al., 2008; Rossberg et al., 2010).

Data analysis

In order to obtain information about **weed occurrence in sugar beet**, data from the SBCS was used. In principle, weeds were categorised as 'common' and 'difficult-to-control' weeds. Difficult-to-control weeds were characterised in case of typical field-specific insufficient controllability with herbicide use strategies calculated on regional scale (Ladewig et al., 2007). Different herbicide use strategies (NEPTUN-survey) and weed infestations (SBCS) were compared for three exemplary regions (Tab. 2). On regional scale one to two ERA were considered as exemplary regions. Only catchment areas which are mostly situated inside an exemplary region were included in this study. Exemplary region 1 approximates the ERA 1001 (Schleswig-Holstein/nördliches Niedersachsen), exemplary region 2 the ERA 1009 (Niederrheinische Bucht/Köln-Aachener Bucht) and exemplary region 3 the ERA 1015/1016 (Nördliche Gäuplatten/Westfranken; Keuper-Lias-Land), respectively. Time lag between both surveys was neglected.

Generally, **the use of non-selective herbicides** was classified into three groups differing in date and development stage of sugar beet when applied. Three categories were determined: Pre-sowing treatments in autumn, pre-sowing treatments in spring, and pre-emergence treatments after sowing in spring. In the NEPTUN-survey, all glyphosate applications after 1st September of the year previous to sugar beet cultivation were included. In the SBCS, glyphosate application was considered for the first time in 2000, but no classification was made. Additionally, the acreage with plough and mulch tillage systems was recorded and set into relation to the use of non-selective herbicides.

In the SBCS, herbicide treatments were classified into two groups, **post-emergence treatments** only and a combination of **pre-/post-emergence treatments**. In the NEPTUN-survey, the date of sugar beet emergence was not recorded. Therefore treatments in a period of up to seven days after sowing were regarded to be pre-emergence. All pre-sowing and pre-emergence treatments were aggregated to pre-emergence treatments in order to improve comparability between both surveys. In Fig. 2, glyphosate-containing herbicide products were included in NEPTUN-survey, only.

The **number of herbicide treatments** was analysed for the two categories of post- and pre-/post-emergence treatments as defined above (NEPTUN and SBCS).

The analysis of the **number of herbicide products used per treatment** (NEPTUN) based on 11,900 treatments resulting from 30,796 herbicide applications. Approximately 99% of all applications resulted from the first five treatments. Hence, data analysis and presentation included the first five treatments only, which led to more compact figures, as well as the use of the 5th/95th percentile. To illustrate differences in the rate of occurrence of herbicide treatments, proportions of fields with the corresponding number of treatments were shown. The number of herbicide products used was calculated from the number of different herbicide products used per field and treatment, while different products were counted separately, even when the active ingredients were identical.

The analysis of the **number of active ingredients per treatment** (NEPTUN) based on 11,900 treatments resulting from the application of added up 46,419 active ingredients. It was calculated by summing up identical active ingredients per field and treatment, while different herbicide products with identical active ingredients were counted once.

The **treatment index** (TI) describes the intensity of pesticides use in the period from harvest of the preceding crop till harvest of the sugar beet (Rossberg et al., 2002).

In this study, the Treatment index$_H$ refers to herbicides only, and was calculated separately for each field (1).

$$\text{Treatment index}_H = \sum \left(\frac{\text{application rate}}{\text{authorised application rate}} \times \frac{\text{treated acreage}}{\text{total acreage of field}} \right) \quad (1)$$

The **treatment frequency** (TF) is defined by the number of pesticide treatments conducted on a certain field, whereas site-specific applications were considered by acreage-coefficient. In this study Treatment frequency$_H$ refers to herbicides only (2).

$$\text{Treatment frequency}_H = \sum \left(\text{number of treatments} \times \frac{\text{treated acreage}}{\text{total acreage of field}} \right) \quad (2)$$

Herbicide use was assigned to four different **herbicide dosage reduction classes** which were classified by frequently used reductions of herbicide products referring to the authorised application rate (NEPTUN). Application rates of identical herbicide products were summed up for each field to 8,713 dosages and were assigned to the classes > *75%*, *50–75%*, *25–50%* and < *25%* of dosage-reduction relative to the authorised application rate.

The relative importance of each **active ingredient** was analysed by calculating both the proportion of applications including the respective active ingredient in relation to all applications, and the acreage treated with each active ingredients percentage of the total treated area (NEPTUN).

Herbicide costs were calculated according to the NEPTUN-data and the pesticide price list of *BayWa AG*, 2009 (ANONYMOUS, 2009b).

Statistical analysis was conducted by the procedure 'proc glm' for analysis of variance followed by a multiple comparison of means according to Tukey (SAS Version 9.2, SAS Institute Inc., Cary, NC, USA).

3 Results

Concerning the common weeds, the spread of knotweed (POLSS) increased continuously from 35% to 86%, goosefoot (CHESS) from 47% to 79% and annual mercury (MERAN) from 9% to 25% in 1996 and 2010, respectively (Tab. 1). The occurrence of cleaver (GALAP) varied constantly around the average of 47% and camomile (MATSS) between 16% and 35%. Regarding the difficult-to-control weeds, knotweed (POLSS) was the most widespread specie. Its proportion constantly increased up to 25% in 2010. Weed beet increased from 4% in 1996 to 9% in 2010. The other weed species remained relatively constant at about 15% or less.

Generally, weed infestation on regional scale was heterogeneous in occurrence and intensity (Tab. 2). Within exemplary region 1, common weeds dominated clearly over difficult-to-control weeds, whereas in exemplary region 2 and 3 the distribution was more balanced between common and difficult-to-control weed species.

Acreage of plough tillage system decreased from 89% in 1994 to 55% in 2010 (Fig. 1). Acreage of mulch tillage system increased proportionally from 11% to 45%, corres-

Tab. 1. Important common and difficult-to-control weeds in sugar beet cultivation, estimated acreage of weed occurrence in % of total acreage. Sugar Beet Cultivation-survey (SBCS), Germany 1996–2010

Weeds	Bayer Code	1996	1998	2000	2002	2004	2006	2008	2010	Mean
Common										
goosefoot	CHESS	47	69	70	67	74	76	77	79	70
knotweed	POLSS	35	39	49	55	67	72	84	86	61
cleaver	GALAP	45	42	47	46	58	53	47	36	47
camomile	MATSS	16	22	33	24	27	31	35	34	28
annual mercury	MERAN	9	3	15	14	18	19	24	25	16
Difficult-to-control										
knotweed	POLSS	11	12	12	16	18	20	26	25	17
annual mercury	MERAN	10	12	14	16	10	13	18	16	14
fool‘s parsley	AETCY	11	8	10	13	12	10	10	10	11
cleaver	GALAP	14	9	6	10	9	8	6	5	8
weed beet	NNNRS	4	4	4	9	12	8	13	9	8
camomile	MATSS	2	5	8	10	13	9	7	6	7
volunteer rape	BRSNN	6	2	5	6	11	5	10	14	7
vol. potatoes	SOLTU	0	0	5	2	2	1	3	2	2

Tab. 2. Important common and difficult-to-control weeds in three exemplary regions of sugar beet cultivation, estimated acreage of weed occurrence in % of total acreage. Sugar Beet Cultivation-survey (SBCS), Germany 2008

Weeds	Bayer Code	Exemplary region 1[1]	Exemplary region 2[1]	Exemplary region 3[1]
Common				
annual mercury	MERAN	–	53	–
black bindweed	POLCO	60	20	70
black nightshade	SOLNI	–	22	–
camomile	MATSS	70	41	–
chickweed	STEME	–	56	36
cleaver	GALAP	90	11	57
common orache	ATXPA	–	–	80
field pansy	VIOAR	80	–	–
fool's parsley	AETCY	–	10	–
knotgrass	POLAV	30	21	1
speedwell	VERSS	70	–	18
volunteer rape	BRSNN	65	–	–
white goosefoot	CHEAL	40	75	–
Difficult-to-control				
annual mercury	MERAN	–	41	8
black nightshade	SOLNI	–	–	3
cleaver	GALAP	–	–	13
common orache	ATXPA	15	–	–
field bindweed	CONAR	–	–	10
field woundwort	STAAR	3	–	–
fool's parsley	AETCY	25	13	11
hemlock	CIOMA	5	–	–
knotgrass	POLAV	–	14	–
barnyard grass	ECHCG	–	6	–
pigweed	AMASS	–	–	15
three-cleft bur-marigold	BIDTR	–	–	5
volunteer potatoes	SOLTU	–	6	–
water smartweed	POLAM	–	5	–
weed beet	NNNRS	–	13	3
white goosefoot	CHEAL	–	4	–

[1] **Exemplary region 1:** Approximating ERA 1001 Schleswig-Holstein/Nördliches Niedersachsen;
Exemplary region 2: Approximating ERA 1009 Niederrheinische Bucht/Köln-Aachener Bucht;
Exemplary region 3: Approximating ERA 1015/1016 Nördliche Gäuplatten/Westfranken; Keuper-Lias-Land

pondingly the acreage of non-selective herbicides increased from 17% in 2000 to 45% in 2010.

The proportion of acreage with post-emergence treatments estimated by the SBCS increased continuously from 80% in 1996 to 89% in 2010, while by the NEPTUN-survey post-emergence treatments were between 70% in 2007 and 80% in 2005 (Fig. 2).

By the SBCS, the number of post-emergence treatments remained relatively constant at approximately 3 (Fig. 3). Pre-/post-emergence treatments increased slightly from 2.9 in 1996 to 3.3 in 2010 (no glyphosate-containing herbicide products were included). In the NEPTUN-survey, post-emergence treatments averaged nearly 3.5 and pre-/post-emergence treatments approximately 4.9, where almost all pre-emergence treatments consisted of glyphosate-containing herbicide products.

Across years, the 1st treatment showed a significantly lower number of herbicide products compared to the 2nd of about 2.5 and 3.0, respectively, while the 3rd treatment remained at a similar level as the 2nd (Fig. 4). The 4th and 5th treatments had a significantly lower number of herbicide products of about 2.2 compared to the other treatments. The differences in herbicide products per treatment between years were not significant.

Across years, the 2nd treatment showed the highest number of active ingredients per treatment of approximately 4.4 compared to the others, while the 1st treatment remained on a similar level as the 3rd of about 4.0

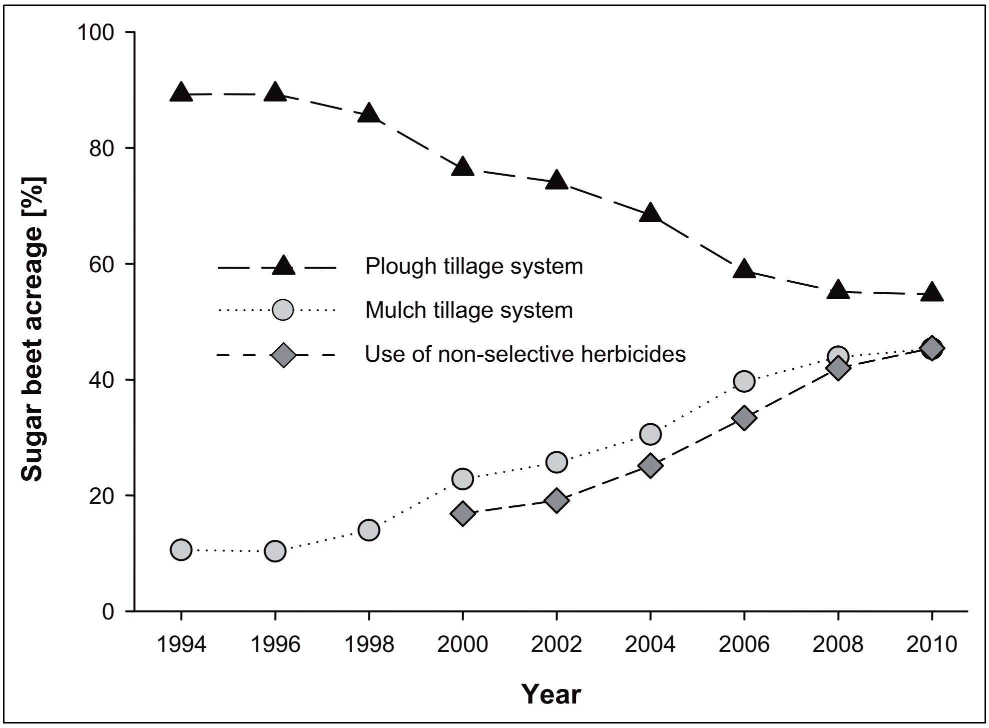

Fig. 1. Tillage systems applied for sugar beet cultivation and use of non-selective herbicides, estimated distribution in % of total acreage. Sugar Beet Cultivation-survey (SBCS), Germany 1994–2010.

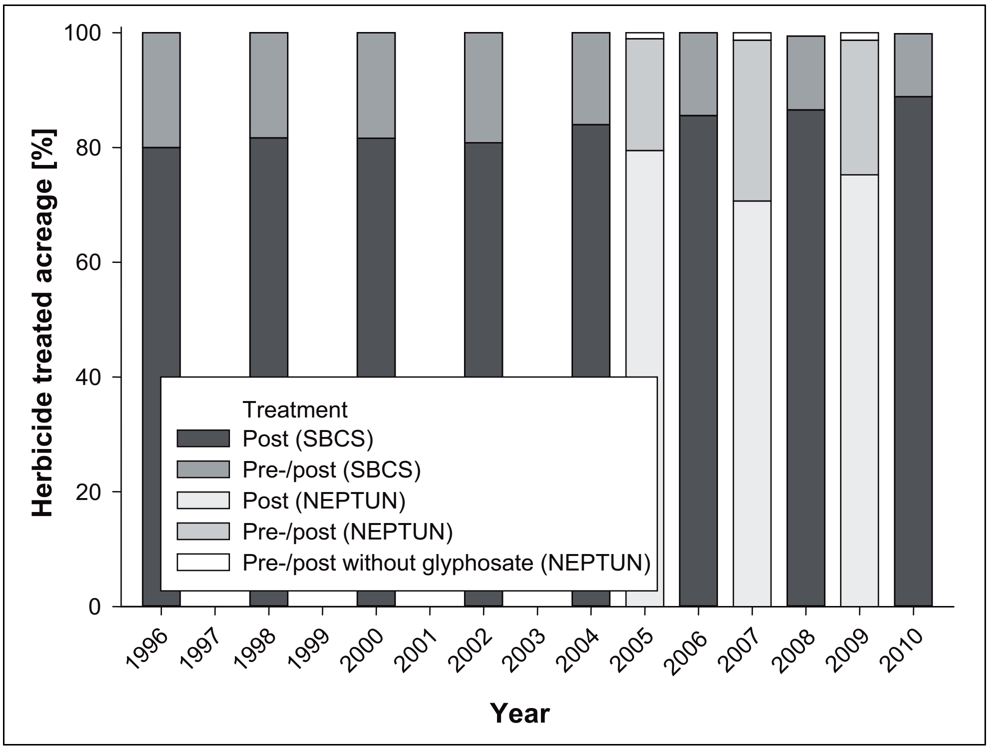

Fig. 2. Post- and pre-/post-emergence herbicide treatments in sugar beet cultivation, estimated (SBCS) and surveyed (NEPTUN) herbicide treated acreage in % of total acreage. Sugar Beet Cultivation-survey (SBCS), Germany 1996–2010 and NEPTUN-survey, Germany 2005–2009.

(Fig. 5). The 4th and 5th treatments showed a significantly lower number of active ingredients of approximately 3.0 compared to the other treatments. The differences in active ingredients per treatment between years were not significant.

The Treatment index$_H$ showed an increasing tendency for the 1st, 2nd and 3rd treatments of about 0.5, 0.6 and 0.7, respectively (Fig. 6). The differences were significant in the years 2007 and 2009. Treatment index$_H$ of the 4th and 5th treatments remained on a similar level as of the 1st treatment. The differences in Treatment index$_H$ per treatment between years were significant in 2005 and 2007.

On average of all dosages, 37% could be assigned to the dosage-reduction class *50–75%* and 29% to the class *25–50%,* followed by the class *> 75%* and *< 25%* with 20% and 14%, respectively, the differences were significant between all classes (Tab. 3). From 2005 to 2009 the

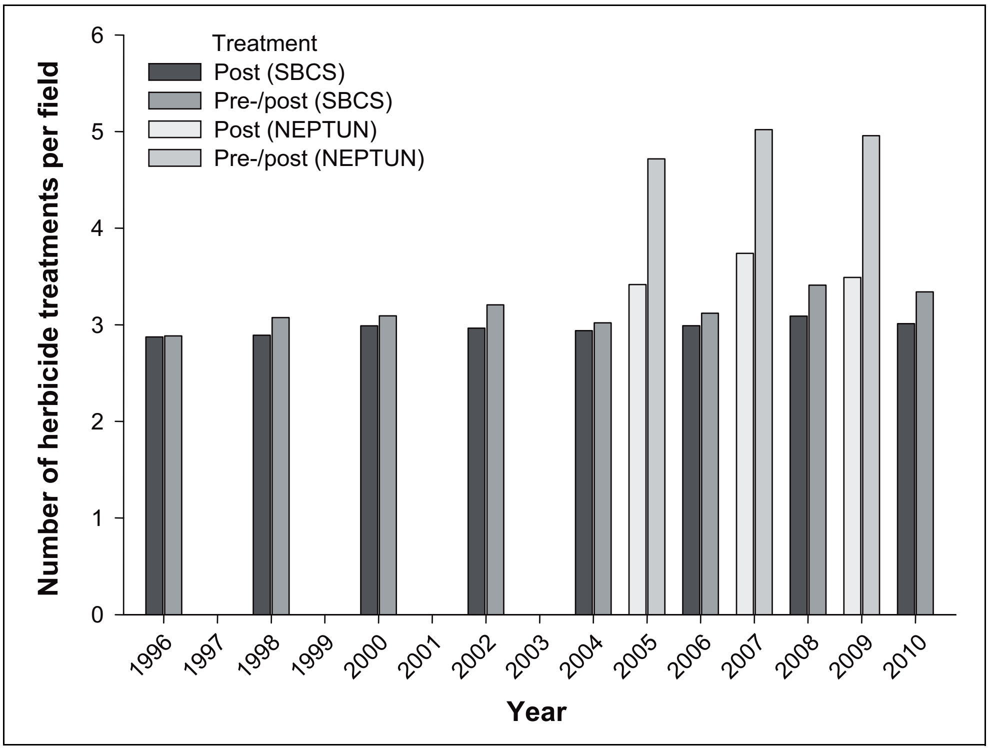

Fig. 3. Number of herbicide post- and pre-/post-emergence treatments per field in sugar beet cultivation, estimated (SBCS) and surveyed (NEPTUN) values. Sugar Beet Cultivation-survey (SBCS), Germany 1996–2010 and NEPTUN-survey, Germany 2005–2009.

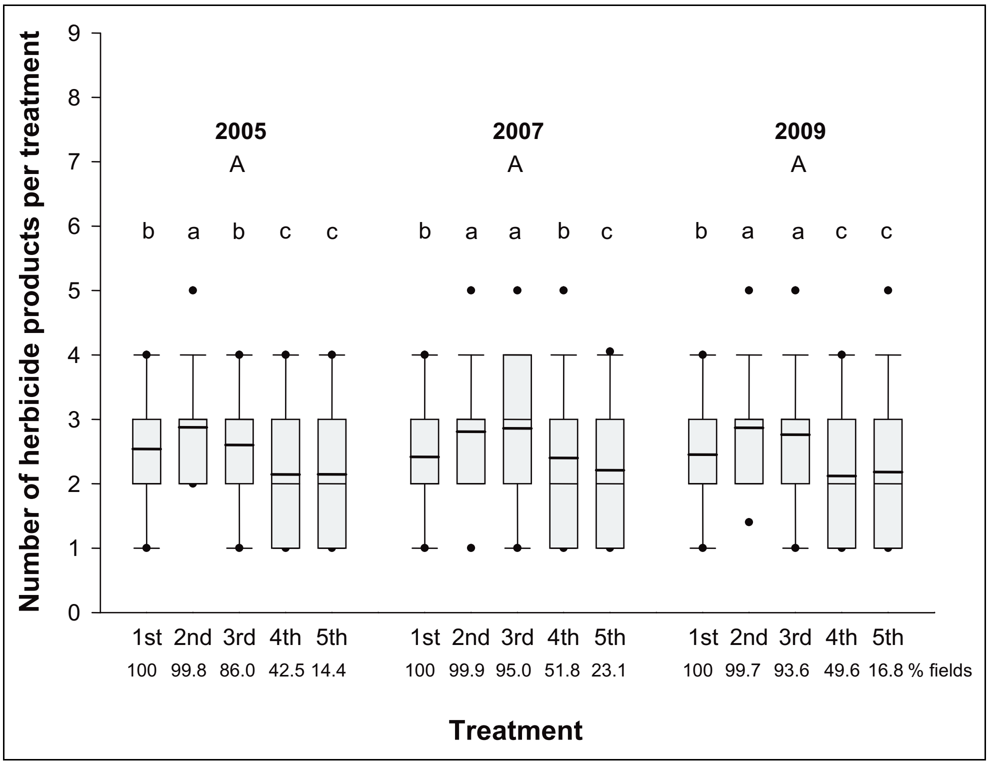

Fig. 4. Number of herbicide products per treatment for the first five post-emergence treatments in sugar beet cultivation, mean/median and the 5th/95th percentile. Different upper and lower case letters indicate significant differences between years, and treatments within each year, respectively. (Tukey-test, $p \leq 0{,}05$). No. = 11,684 treatments, NEPTUN-survey, Germany 2005–2009.

proportion of the class *50–75%* significantly decreased, however, the class < *25%* and *25–50%* significantly increased, while differences within the class > *75%* were not significant.

Ethofumesate, phenmedipham and metamitron were applied on nearly the total acreage and desmedipham on about 70%, representing about 3/4 of all herbicide applications (Tab. 4). Approximately 1/2 of the acreage was treated with triflusulfuron, chloridazon and quinmerac. Proqaquizafop, fluazifop-P and quizalofop-P were used on < 20% of the acreage in order to control monocotyledons.

The treatment frequency$_H$ of fields with pre-/post-emergence treatments differed between the observed

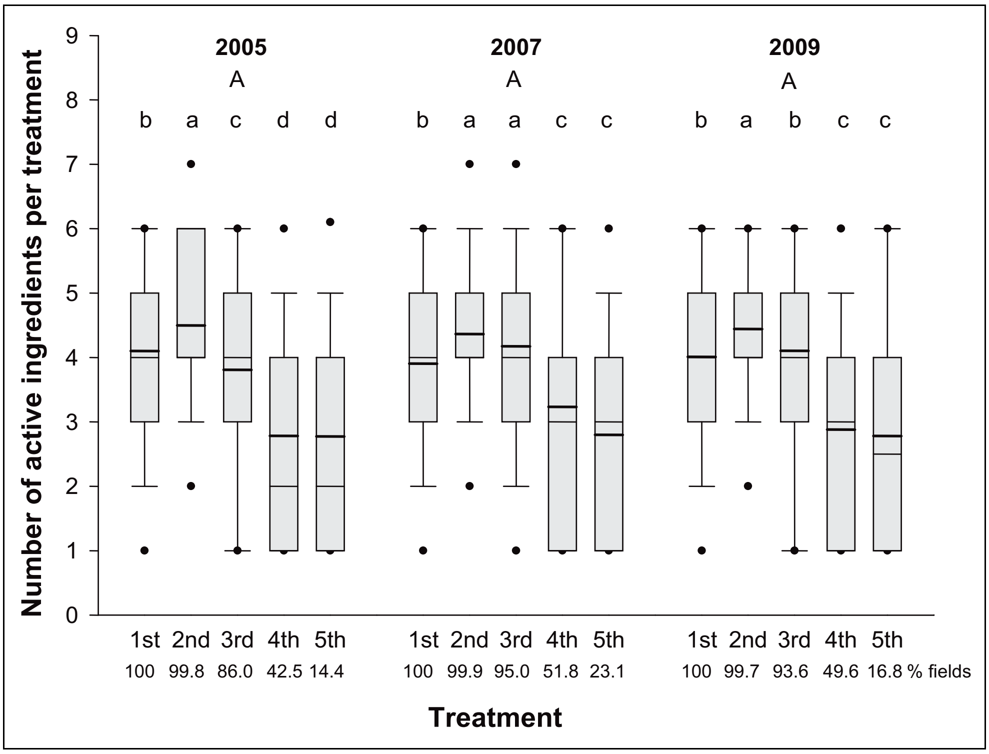

Fig. 5. Number of active ingredients per treatment for the first five post-emergence treatments in sugar beet cultivation, mean/median and the 5th/95th percentile. Different upper and lower case letters indicate significant differences between years, and treatments within each year, respectively. (Tukey-test, $p \leq 0{,}05$). No. = 11,684 treatments, NEPTUN-survey, Germany 2005–2009.

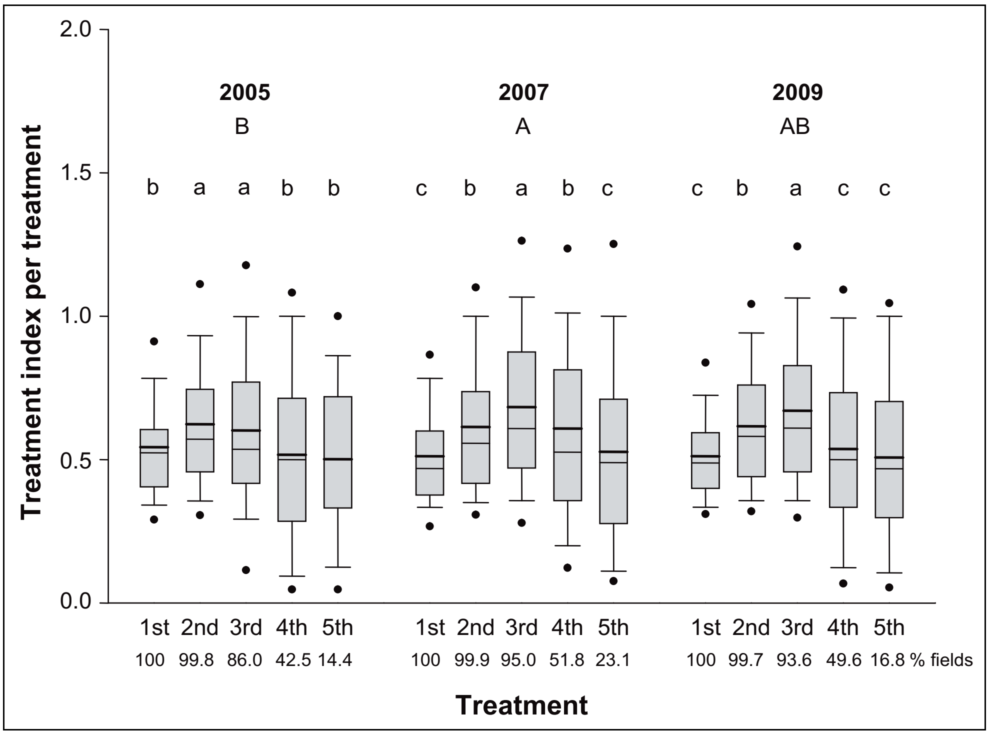

Fig. 6. Treatment index$_H$ for the first five post-emergence treatments in sugar beet cultivation, mean/median and the 5th/95th percentile. Different upper and lower case letters indicate significant differences between years, and treatments within each year, respectively. (Tukey-test, $p \leq 0{,}05$). No. = 11,684 treatments, NEPTUN-survey, Germany 2005–2009.

ERA from 2.5 to 6.3, on average 5 treatments were done per field (Tab. 5). 2.9–4.5 treatments were done per field with post-emergence treatments only. The 1st treatment was applied on average 15 days after sowing, varying from 12 to 21 days between the ERA followed by a mean treatment interval from approximately 12 days varying from approximately 8 to 15 days. On average, 2.6 herbicide products and 4.1 a.i. were applied per treatment, varying from 2.2 to 3.5 herbicide products and 3.6 to 4.8 a.i., respectively. This resulted in a treatment index$_H$ of 2.05 on average, varying from 1.47 to 2.51. Herbicide costs were on average 213 €/ha, varying from 177 €/ha–251 €/ha. 35% of all dosages in 2009 could be assigned to the dosage-reduction class *50–75%* varying from 27% to 43%, 33% to the class *25–50%* varying from 25% to 51%. The dosage-reduction class > *75%* and < *25%* were

Tab. 3. Herbicide use in sugar beet cultivation. Proportion of dosage-reduction relative to authorised application rate in % of all applications. Upper and lower case letters are related to differences within and between the dosage-reduction classes, respectively (Tukey-test, p ≤ 0,05). 15,996 applications. NEPTUN-survey, Germany 2005–2009

Classes	2005	2007	2009	Average
	% of all applications			
Dosage-reduction > *75%* relative to authorised application rate	19.9^{A}	20.7^{A}	19.2^{A}	19.9^{c}
Dosage-reduction between *50–75%* relative to authorised application rate	39.8^{A}	36.8^{B}	34.7^{B}	37.3^{a}
Dosage-reduction between *25–50%* relative to authorised application rate	27.8^{B}	26.9^{B}	32.6^{A}	29.1^{b}
Dosage-reduction < *25%* relative to authorised application rate	12.5^{C}	15.7^{A}	13.5^{B}	14.0^{d}
$\sum$	100	100	100	

Tab. 4. Proportion of active ingredients used in herbicide applications (A) and proportion of treated acreage (B) in sugar beet cultivation. 15,125 applications of active ingredients, 11,585 ha total acreage. NEPTUN-survey, Germany 2009

Active ingredient	A* [%]	B [%]
ethofumesate	20.9	99.8
phenmedipham	20.3	99.8
metamitron	21.2	99.8
desmedipham	13.4	72.4
triflusulfuron	5.2	59.4
chloridazon	5.6	44.3
quinmerac	5.5	44.2
glyphosate**	1.6	28.6
propaquizafop	1.0	16.8
fluazifop-P	1.5	13.0
clopyralid	1.2	10.0
dimethenamid-P	1.5	8.2
quizalofop-P	0.6	4.2

* ≥ 0.5%; ** pre sowing-applications included

assigned to 19% and 14%, varying from 8% to 26% and 10% to 20%, respectively.

4 Discussion

Over the past five decades, herbicide use strategies in sugar beet cultivation evolved by the development of new active ingredients (a.i.) and in the mid 1980s by specific development of herbicide use strategies. Hence, herbicide use got more and more sophisticated depending on field- and regionally-specific weed population. Generally, public's criticalness against pesticide use induced National Action Plans (BMVEL, 2004; BMELV, 2008) which increased transparency and documentation of pesticide use. In the present study, data from surveys was evaluated and analysed aiming at (i) the species-specific compositions of weed populations and (ii) the different herbicide use strategies on regional scale in Germany. Therefore, two different basic approaches were approved, 'Sugar Beet Cultivation-survey (SBCS) 1994–2010' containing estimated key figures of pesticide use and weed control, and NEPTUN-survey 2005, 2007 and 2009 containing data of pesticide use on field scale.

Methodological critique concerning the quantitative analysis of surveys refers to size, distribution and mode of taking the sample. Experts estimation in SBCS leads to a good overview of many aspects with a more regional character e.g. weed infestation, for which an enormous amount of data is compulsory when evaluated field-specifically. Otherwise, precision might be lower for specific aspects like e.g. treatment frequency or treatment interval of herbicide use. These aspects were generated precisely by using results of the NEPTUN-survey on farm scale. For regional analysis of NEPTUN-data at least 30 samples were used compared to the SBCS where data was estimated by local sugar factory advisers. Estimation of experts might be of low reliability, particularly if catchment areas are relatively large. However, comparative analysis of many aspects of both surveys resulted in high coincidence (BUHRE et al., 2011).

Data analysis on national scale

Generally, **weed infestation in sugar beet** is influenced by e.g. soil characteristics (NORDMEYER and NIEMANN, 1992; PETERSEN, 2004) tillage system (PRINGAS et al., 2001), management intensity (WAGENITZ and MEYER, 1981), fertilisation (BRÄUTIGAM and SCHÄUFELE, 1994), crop competitiveness (KUDSK, 2008), climate (KUDSK, 2008) and herbicide use (BACHTALER and DANCAU, 1970; SCHÄUFELE, 2000; PETERSEN, 2004). Goosefoot (CHESS) was the most significant weed in sugar beet (PETERSEN and HURLE, 1998). This is consistent with the data of the SBCS in which goosefoot was found on approximately 70% of sugar beet acreage. Evaluated from the SBCS 1996–2010, knotweeds (POLSS), chamomile (MATSS) and annual mercury (MERAN) as common weeds increased to 86%, 34% and 25% of the acreage, respectively. This goes along with an increase of mulch tillage in sugar beet cultivation (Fig. 1) which led to a higher content of organic matter in topsoil

Tab. 5. Key figures of herbicide use strategies in weed control on a regional scale (ERA): treatment frequency, number of herbicide products (hp) per treatment, number of active ingredients (a.i.) per treatment, herbicide treatment index (TI_H), herbicide cost and proportion of dosage-reduction relative to authorised application rate (% of all applications), NEPTUN-survey, Germany 2009

	Fields	ERA[1]					
	Ø	1001	1009	1015	1016	min[2]	max[2]
		e.r. 1[3]	e.r. 2[3]	e.r. 3[3]			
Treatment frequency$_H$ (pre-/post-emergence)	5.0	6.3	5.0	2.5	4.0	2.5	6.3
Treatment frequency$_H$ (post-emergence)	3.5	4.5	3.6	2.9	3.0	2.9	4.5
First treatment [days after sowing]	15.0	15.0	16.1	17.6	15.3	12.2	20.9
Mean treatment interval (treat. 1–3) [days]	12.4	7.9	11.7	15.4	11.9	7.9	15.4
Mean treatment interval (treat. 1–5) [days]	12.3	8.8	11.2	14.4	11.8	8.8	14.4
Number of hp per treatment (treat.1–5)	**2.6**	**2.7**	**3.5**	**2.6**	**2.2**	**2.2**	**3.5**
No. of herbicides 1st treatment	2.6	2.4	3.6	2.6	2.2	2.0	3.6
No. of herbicides 2nd treatment	2.9	2.9	4.2	2.8	2.2	2.2	4.2
No. of herbicides 3rd treatment	2.8	3.0	3.5	2.3	2.3	2.3	3.5
No. of herbicides 4th treatment	2.1	2.5	2.2	2.2	1.2	1.2	2.9
No. of herbicides 5th treatment	2.2	2.5	2.2	1.5	–	1.0	3.0
Number of a.i. per treatment (treat. 1–5)	**4.1**	**3.6**	**4.8**	**4.5**	**4.1**	**3.6**	**4.8**
No. of a.i. 1st treatment	4.3	3.3	5.6	4.9	4.4	3.3	5.6
No. of a.i. 2nd treatment	4.6	4.0	5.8	5.0	4.2	4.0	5.8
No. of a.i. 3rd treatment	4.3	4.0	4.3	3.7	4.3	3.7	4.6
No. of a.i. 4th treatment	2.9	3.2	2.8	3.0	1.6	1.6	4.2
No. of a.i. 5th treatment	2.9	3.2	2.6	2.0	–	1.0	5.0
Treatment index$_H$ (treat. 1–5)	**2.05**	**2.09**	**2.51**	**1.82**	**1.47**	**1.47**	**2.51**
TI_H 1st treatment	0.52	0.46	0.59	0.52	0.42	0.41	0.60
TI_H 2nd treatment	0.62	0.52	0.82	0.62	0.47	0.44	0.82
TI_H 3rd treatment	0.67	0.54	0.83	0.77	0.59	0.54	0.83
TI_H 4th treatment	0.54	0.42	0.46	0.91	0.53	0.37	0.91
TI_H 5th treatment	0.51	0.40	0.47	0.73	–	0.40	0.92
Herbicide cost [€/ha]	**213**	**216**	**211**	**193**	**177**	**177**	**251**
Dosage-reduction relative to authorised application rate	**2009 Ø**	**proportion of all herbicide applications [%]**					
Dosage-reduction > 75%	19.2	19.9	20.9	17.9	7.6	7.6	26.2
Dosage-reduction between 50–75%	34.7	27.8	41.0	43.0	29.1	27.2	43.0
Dosage-reduction between 25–50%	32.6	32.5	24.7	29.1	51.3	24.7	51.3
Dosage-reduction < 25%	13.5	19.9	13.4	9.9	12.0	9.9	19.9

[1] **ERA** 1001: Schleswig-Holstein/Nördliches Niedersachsen; 1009: Niederrheinische Bucht/Köln-Aachener Bucht; 1015: Nördliche Gäuplatten/Westfranken; 1016: Keuper-Lias-Land
[2] min/max referring to all 15 ERA in Germany
[3] (e.r.) approximating exemplary regions 1, 2 and 3

(Jacobs et al., 2009) and a slower soil warming. Increasing organic matter might decrease efficacy of residual acting active ingredients, while soil temperature is the most important factor for early growth of sugar beet (Krause et al., 2009) which is linked to the competitiveness against weed. While the proportion of common weeds increased, difficult-to-control weeds were relatively constant at 2–17% of the acreage with the exception of knotweeds (POLSS), weed beet (NNNRS) and volunteer rape (BRSNN) which varied from 2–26% across the years. This could be partially explained by the increasing proportion of oil seed rape in crop rotations with sugar beet of approximately 20% of the acreage (SBCS, not shown). Weed beet was found frequently in rotations with a high proportion of sugar beet (Longden, 1993). Annual meadow-grass (POAAN) and wild-oat (AVEFA) were the most common annual grass weeds but gramineous were less important in weed control than most of the broad-leave weeds (KNOTT, 2002; PETERSEN, 2004).

In the last decades, **herbicide strategies** were evolved towards split-applications and post-emergence treatments. Post-emergence treatments increased from 6% in 1980 to 62% in 1992 (ZINK et al., 1994) and in the SBCS from approximately 80% in 1996 to 90% in 2010 (Fig. 2). The NEPTUN-survey even indicated post-emergence proportion > 98% of the acreage in 2005–2009 (Fig. 2) if glyphosate use is not considered as it was done in SBCS. The use of pre-emergence treatments resulted in a higher total number of herbicide treatments per field of approximately 5.0 (including glyphosate) compared to approximately 3.5 when applied solely post-emergence (Fig. 3). According to SCHÄUFELE (2000) and KUDSK (2002), on average 3–3.5 treatments were applied predominantly to control annual broad-leave species and to compensate less efficacy of post-emergence herbicides. Usually, 3 treatments led to a sufficient weed control efficacy > 95% if they were adapted and timed precisely to field-specific weed population (BRUNS et al., 2008; VASEL et al., 2011).

Across the last 15 years, **treatment patterns of herbicides** were similar although spread of weeds like goosefoot (CHESS) and knotweed (POLSS) increased from 47 and 35% to 79 and 86%, respectively. The 1st treatment was usually applied approximately 15 days after sowing, varying from 12–21 days, depending on weed species, weed emergence and weather conditions. Between the years, a similar trend was observed in **number of herbicides and active ingredients used per treatment** for the first five treatments. The 1st treatment consisted of approximately 2.5 herbicides followed by 3, 3, 2, and 2 to the 5th treatment (Fig. 4). 4 active ingredients were used in the 1st treatment followed by 4.5, 4, 3, and 3 to the 5th treatment (Fig. 5). Meanwhile the **treatment index$_H$** of the first three treatments (Fig. 6) increased from 0.5 to 0.7, which could be explained by more weed species in later developmental stages of the sugar beet as well as less sensitiveness of more developed sugar beet and weeds (WINNER, 1981). The treatment index$_H$ decreased in the 4th and 5th treatments, each, to approximately 0.5 in relation to 2 herbicide products and 3 active ingredients used per treatment (Fig. 4, Fig. 5). The treatment index$_H$ showed significant differences between the years (Fig. 6). Consequently, the adaption of changing weed infestation was encountered by different herbicide use intensity but consistent treatment patterns on national scale (Fig. 4, Fig. 5). This could be an adaption to seasonal effects like drought, coldness as well as efficacy and selectivity of active ingredients etc. which influence the time of canopy closure and thus the competitiveness of the sugar beet against weeds (WINNER, 1981; KOBUSCH, 2003).

Considering the generally low treatment index per treatment and the proportional dosage reductions, it becomes obvious that only few dosages were applied at authorised rate. Therefore, emphasis of weed control was not put on the exhaustion of authorised application rates but on the combination of various herbicide products with their altering active ingredients. This process of dosage-reduction and split-applications over the past three decades was also driven by reducing costs of herbicide treatments.

The active ingredients ethofumesate, phenmedipham and metamitron as well as desmedipham were most widespread in weed control which represent approximately 75% of all herbicide applications, and were applied on almost the total acreage. These active ingredients could control almost every common or standard weed infestation in sugar beet crop. Difficult-to-control weeds or specific weed species like annual mercury (MERAN), three-cleft bur-marigold (BIDTR) or volunteer rape (BRSNN) require additional active ingredients like triflusulfuron or chloridazon & quinmerac which were used on approximately one half of the acreage. Efficacy and the composition of these active ingredients are mainly influenced by weather conditions. At dry conditions a higher proportion of contact acting active ingredients e.g. phenmedipham, clopyralid or triflusulfuron are required. However, favourable conditions give an advantage to residual acting active ingredients e.g. chloridazon, dimethenamid-P, ethofumesate or metamitron. Generally, efficacy and therefore the potential decreasing application rates increase with better environmental conditions and thus the treatment index$_H$ per treatment decreases. Regulating **weed beet** in sugar beet is limited to non-selective a.i. like glyphosate (LONGDEN, 1993). Compared to this, selective a.i. like sulfonylurea or growth promoters could be used to control weed beet in cereals more easily.

Thresholds for weed control in sugar beet were examined but could not be used for most weeds because of low efficacy and high cost of herbicides to control most tall weeds (BRÄUTIGAM, 1998; WELLMANN, 1999). Hence, split weed control in the very early stage of weed development could reduce application rates > 75% compared to the authorised application rate. Reduced dosages minimise physiological stress for sugar beet plants (BEISSNER, 2000) and could have economic and ecological benefits by using fewer amounts of herbicides. These split-applications of herbicide products are unique in sugar beet cultivation compared to other crops.

Data analysis on regional scale

Weed population on regional scale varied widely compared to national scale. This refers to the results of 2008 which were in between of the NEPTUN-survey 2007 and 2009. Regional differences in herbicide use and weed population are demonstrated by three exemplary regions (Tab. 2, Tab. 5). Volunteer rape (BRSNN) occurred on approximately 65% of the acreage in the **exemplary region (1)** *Schleswig-Holstein/Nördliches Niedersachsen*. The herbicide use strategy focused on a higher treatment frequency$_H$ of 4.5, a shorter treatment interval of 8–9 days, a mean number of 2.7 herbicide products and 3.6 active ingredients per treatment. The treatment index$_H$ and costs were 2.09 and 216 € ha^{-1} on average, respectively. This led to sufficient efficacy to control volunteer rape (BRSNN) by treating continuously emerging plants in the sensitive cotyledon stage. The relatively high treatment frequency$_H$ and average number of herbicides led to a proportion of applications of approximately 20% of *dosage reduction group < 25%*. A proportion of applications of approximately 28% were surveyed for *dosage reduction group 50–75%* compared to the authorised application rate. In the **exemplary region (2)** *Niederrheinische Bucht/Köln-Aachener Bucht* annual mercury (MERAN) was the most widespread difficult-to-control weed. It was recorded on > 40% of the acreage. 3.5 herbicide products and 4.8 active ingredients were used which is approximately 1 more than the average. Triflusulfuron was widely used to control annual mercury (MERAN) which resulted in a higher treatment index$_H$ per treatment > 0.8, especially in the 2nd and 3rd treatment. This led to a 0.5 higher treatment index$_H$ of 2.51 compared to the national average and herbicide costs of 211 € ha^{-1} on average. In spite of the highest treatment index$_H$ in this region, only 13% of applications can be assigned to a dosage reduction class *< 25%*. More than 60% of applications can be assigned to dosage-reduction classes *50–75%* and *> 75%*. Therefore, the change in herbicide practice is based on the extension of the range of efficacy in connection with a slight reduction of intensity of the other herbicide products. The **exemplary region (3)** *Nördliche Gäuplatten/Westfranken; Keuper-Lias-Land* was characterised by the lowest herbicide intensity with a treatment index$_H$ of 1.5–1.8 compared to the average of 2.05. Common weed infestation was relatively low and proportion of difficult-to-control weed was < 15% for a single species. The mean treatment interval, number of herbicides and number of active intgredients per treatment were close to the average of all regions. Compared to this, treatment frequency$_H$ was the lowest with 2.9–3.0. Thus, a lower treatment index$_H$ originated from a lower treatment index$_H$ per treatment and a lower treatment frequency$_H$. An adequate efficacy was reached by higher application rates of herbicide products. This can be seen in the high proportion of dosage-reduction classes *25–50%* and *< 25%*. This factor together with the relatively widespread use of hoeing machines of 20 to 65% of the acreage resulted in the lowest herbicide costs of 177–193 € ha^{-1} compared to approximately 5% and 212 € ha^{-1} on national average, respectively.

Future developments and public acceptance

Alternative herbicide strategies were provided by genetically modified herbicide tolerant (GMHT) sugar beet varieties (MÄRLÄNDER, 2005), which were grown on approximately 95% of Canada's and USA's acreage in 2011 and > 10% of world's sugar beet acreage in 2010 (TRANSGEN, 2011). Tolerance against glyphosate promises to decreases eco-toxicity and would positively influence economic and environmental parameters (DEWAR et al., 2003; MÄRLÄNDER, 2005). It enables the use of thresholds for weed control which results in lower herbicide intensity compared to weed control with conventional herbicides (Tab. 6) (MÄRLÄNDER and VON TIEDEMANN, 2006). Cultivating GMHT varieties and the corresponding application of glyphosate simplifies herbicide treatment by more flexibility in timing and obviates the need of herbicide mixtures (KNOTT, 2002). Although, specific cases e.g. late weed infestations or anti-resistance strategies may require additional selective a.i. as mixture partners. Reflecting MAY (2003), MÄRLÄNDER (2005), KNISS (2010) and own calculations, savings for herbicide treatments in GMHT-systems were approximately 80 € ha^{-1} compared to conventional practice. Consequently, GMHT-systems would introduce new possibilities for Integrated Pest Management and sustainable development (MÄRLÄNDER et al., 2003), however, GMHT-system is not accepted by public in Germany. For the conventional system, neither new active ingredients were developed in the last two decades, nor are active ingredients in preparation by now. An exception is the reapproved active ingredient lenacil which is a 'new' application partner since 2011.

Tab. 6. Cost and intensity of weed control by herbicides in sugar beet. Costs are based on NEPTUN-survey data and *BayWa AG* price list from 2009. GMHT (genetically modified herbicide tolerant) is calculated by the authorised application rate; application cost amended after KTBL 2008/2009

	Conventional system	GMHT-system
Herbicide cost	213 € ha^{-1}	70 € ha^{-1}
Application cost	3.5*15 €	2*15 €
Seed royalty+	—	80 € ha^{-1}
$\sum$	258 € ha^{-1}	180 € ha^{-1}
Treatment index	2.25	1.00

+ Data from USA (PATTERSON, 2009)

Mechanical weed control by tractor hoeing is an alternative measure in weed control reducing herbicide intensity. Using this technique, the adverse side effects e.g. damage of plant leaves and increasing risk of soil erosion have to be taken into account (GUMMERT et al., 2012), while tractor hoeing had a low efficacy of intra-row weed control (KOUWENHOVEN et al., 1991). However, reducing herbicide input leads to lower herbicide costs of up to 100 €/ha, but increasing costs for labour, even hand-labour and machinery in total.

Today's and future topics in sugar beet cultivation concerning pesticide use and its public acceptance may be realised, inter alia, by the National Action Plan on Sustainable Use of Plant Protection Products (BMELV, 2008) and the introduction of the respective Guidelines for Integrated Pest Management in Sugar Beet Cultivation (GUMMERT et al., 2011). The implementation of the general principles of Integrated Pest Management has to be followed for it, but not all principles are relevant in sugar beet cultivation. Relevant in weed control are preventive measures, monitoring, direct control, reduction to necessary minimum and documentation. However, anti-resistance strategies, non-chemical measures and threshold values are of lower importance. A tool to increase public acceptance towards pesticide use is to monitor the status quo of its application. This was realised by NEPTUN-surveys for sugar beet cultivation till 2009 and it will be done by the Panel of Plant Protection (PaPa) from 2010 to 2014 in connection with monitoring of the particular weed infestation. By focusing on risk reduction instead of application rates of pesticides in general, both profitability and ecological impact could be improved in the sense of a sustainable development.

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