

Changes in Weed Communities, Herbicides, Yield Levels and Effect of Weeds on Yield in Winter Cereals Based on Three Decades of Field Experiments in South-Western Germany

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Received: 25 July 2014 / Accepted: 1 October 2014 / Published online: 20 November 2014
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Abstract Arable cropping practices including chemical weed control changed considerably over the last decades in south-western Germany affecting weed communities and weed-crop interference.

Data of weed control experiments in winter cereals were analysed to determine changes in weed frequencies, applied herbicides and yield over the last three decades. The effect of weeds on yield and economic thresholds (ETs) were determined based on 122 trials for wheat and barley.

In the 1980s, herbicides belonging to the HRAC-groups C, K, M and O; in the 1990s and 2000s to the HRAC-groups A, B and F were dominant. Nevertheless, weed communities were rather stable in winter cereals. *Galium aparine* and *Stellaria media* decreased in frequency. *Alopecurus myosuroides* frequency increased but densities remained stable. ETs ranged from 9.2 to 9.8% and 4.5 to 8.9% absolute weed coverage for wheat and barley correspondingly. Without weed interference yield increased by 0.16 t ha⁻¹ a⁻¹ for wheat and 0.08 t ha⁻¹ a⁻¹ for barley. In the control plots, where weeds competed with the crop, yields did not increase. Yields in the “best” herbicide treatment were 1.5–2.3 t ha⁻¹ higher than in the control plots. This emphasizes the importance of effective weed control in winter cereals.

Keywords *Alopecurus myosuroides* · Economic weed thresholds · Multi-site · Multi-year · Weed coverage · Winter wheat · Winter barley · Yield loss

Veränderungen der Unkrautgesellschaft, der eingesetzten Herbizide, den Kornerträgen und Ertragsverlusten durch Unkrautkonkurrenz in Wintergetreide in den letzten 30 Jahren in Südwestdeutschland

Zusammenfassung In Südwestdeutschland unterlagen die landwirtschaftliche Praxis und insbesondere die chemische Unkrautkontrolle während der letzten Jahrzehnte einem starken Wandel und dadurch auch die Unkrautgesellschaften und die Unkraut-Kulturpflanzen Interaktion.

Unkrautbekämpfungsversuche über 30 Jahre an verschiedenen Standorten in Baden-Württemberg wurden ausgewertet, um Veränderungen in der Unkrauthäufigkeit, den applizierten Herbiziden und dem Ertrag in den letzten drei Jahrzehnten zu untersuchen. Die Unkrautertragswirkung und ökonomische Schadschwellen (ES) wurden anhand von 122 Weizen- und Gerstenversuche bestimmt.

In den 80-ern wurden Herbizide aus den HRAC-Gruppen C, K, M und O und in den 90-ern und ab 2000 aus den Gruppen A, B und F überwiegend eingesetzt. Dennoch blieben die Unkrautgesellschaften relativ stabil. Die Häufigkeit von *Galium aparine* und *Stellaria media* nahm ab. Die Stetigkeit von *Alopecurus myosuroides* hingegen nahm zu, dessen beobachteten Dichten blieben jedoch konstant. Die ES betragen 9,2 bis 9,8% Unkrautbedeckung für Weizen und 4,5 bis 8,9% für Gerste. Ohne Unkrautkonkurrenz nahm der Weizenertrag um 0,16 t ha⁻¹ a⁻¹ und der Gerstenertrag um 0,08 t ha⁻¹ a⁻¹ zu. In den unbehandelten Kontrollparzellen mit Unkrautkonkurrenz konnte keine Er-

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tragszunahme beobachtet werden. Der Ertrag der “besten” Herbizidvariante lag 1,5 bis 2,3 t ha⁻¹ über dem Ertrag der unbehandelten Kontrolle. Eine wirksame Unkrautbekämpfung in Wintergetreide ist daher unabdingbar.

Schlüsselwörter *Alopecurus myosuroides* · Ökonomische Unkrautschadsschwellen · Unkrautbedeckung · Winterweizen · Wintergerste, · Ertragsverlust

Introduction

European agriculture experienced substantial changes and intensification in the last decades. Number of farms decreased and average farm size increased accompanied with reduction of landscape diversity and simplification of crop rotation (Stoate et al. 2001; Robinson and Sutherland 2002; Meyer 2013). In south-western Germany number of farms decreased from about 143,800 in 1981 to 43,400 in 2011 and average farm size increased from 10.6 to 32.8 ha in the same time period (Anonymous 2014a). Changes in crop rotation were mainly associated with increasing share of winter annual crops. Maize was the only summer annual crop that increased in acreage (Andreasen and Streibig 2011; Meyer 2013). Further, yield levels progressed considerably over time: Winter wheat yield increased by 71 kg ha⁻¹ a⁻¹ between 1990 and 2006 in Germany (Hartmann 2008). For winter barley a yield increase of 72 kg ha⁻¹ a⁻¹ was observed over the last five decades in the same region (Ahlemeyer et al. 2008). Breeding and improved cropping practices including weed control play an important role to sustain these yield increases (Rabbinge and van Diepen 2000). Weed control was primarily done with herbicides for the last decades in Europe. Yet available herbicides changed considerably over time. Selective auxin herbicides were introduced in the 1940s controlling broadleaved weeds in cereals. The herbicidal properties of S-triazines, bipyridyliums (diquat and paraquat) and ureas (e.g. monuron) were discovered in the 1950s. In the 1970s ACCase inhibitors targeting the enzyme acetyl-CoA carboxylase and controlling grass weeds were introduced (Kudsk and Streibig 2003). In the same time period, glyphosate a non-selective herbicide was developed. It allowed to control perennial weeds and became an integral component of low and no-till cropping systems. In the 1980s ALS-inhibitors were introduced. They inhibit the acetolactate synthase and thus block the synthesis of branched amino acids. These active ingredients (AIs) are effective at very low dose (Kudsk and Streibig 2003; Kraehmer 2012). Launches of new herbicide groups cause shifts in herbicide use. Hyvönen et al. (2003) found MCPA and other phenoxy acids to be dominant in the 1980s in spring cereals in Finland; a decade later the use of ALS-inhibitors was prevalent.

These developments in chemical weed control and the described changes in agriculture influence weed species frequencies, resulting predominantly in less diverse weed communities (Stoate et al. 2001; Marshall et al. 2003; Andreasen and Streibig 2011; Meyer 2013). For example, the first selective ALS-inhibitor compound chlorsulfuron did not control well *Viola arvensis* and therefore, this weed species became very abundant in Scandinavia and Finland until an effective ALS-inhibitor became available (Andreasen and Streibig 2011).

Changes in weed community may also affect economic threshold levels (ETs). Certain weed species are more expensive to control or cause higher yield losses. Economic thresholds provide simple decision rules based on average weed infestation assessments, to determine whether herbicide application is warranted or not at the field level (Coble and Mortensen 1992). Threshold levels are given for weed groups such as grass weeds, broadleaved weeds or for single weed species such as cleaver (*Galium aparine* L.) (Gerowitt and Heitefuss 1990). In several European countries, ETs must be applied for weed control decisions according to Good Agricultural Practice and plant protection guidelines (PflSCHG § 3; regulation 2009/128/EG, Annex III). ETs need to be exceeded before herbicides are to be applied. In Germany, ETs for cereal crops were established and validated in the 1970s and 1980s (Niemann 1981; Gerowitt and Heitefuss 1990). Given the dramatic changes in agricultural practices, changes in costs for weed control and grain prices, increases of yield levels, potential shifts in weed communities and the requirement by law to employ ETs, re-determination of these important values for weed management using more recent datasets is of high relevance for cereal production.

Weed species frequencies and changes thereof have been investigated in several studies comparing weed surveys from different time periods (e.g. Chancellor and Froud-Williams 1984; Hyvönen et al. 2003; Andreasen and Streibig 2011; Meyer 2013). Multi-site field experiments assessing herbicide efficacy and selectivity carried out over three decades provide an excellent source of data to investigate changes in weed communities, yield levels and herbicide use over time. They also help understanding the impact of cropping systems on weed species communities and weed-crop interactions and the findings may be transferred to other areas with similar cropping practices. This study aimed to (i) investigate changes in weed frequencies and herbicide strategies in winter wheat (*Triticum aestivum* L.) and winter barley (*Hordeum vulgare* L.); (ii) determine the effects of weeds on yield; (iii) calculate current ETs and (iv) determine yield trends for south-western Germany.

Materials and Methods

Database and Experimental Details

Data from field trials published almost annually in the ‘green booklet’ series since 1969 (Schwerdtle et al. 1969; Koch and Kemmer 1972–1982; Hurlle and Kemmer 1983–1997; Hurlle 1998–2004; Gerhards 2005–2011) were assembled for winter wheat and winter barley and used for analyses. Experiments with distinct treatments and research questions were repeated at several sites within south-western Germany over several years. All field trials were designed as randomized complete block design with four replicates. Plot size was 2–3 m by 6–10 m. Herbicides were sprayed with a plot sprayer. Trials were harvested with plot combines. Field trials and data recording were carried out according to good experimental practice (GEP). Weed and crop coverage was estimated at the day of herbicide application and several times thereafter to assess herbicide efficacy. Weed species, weed and crop coverage as head density of *Alopecurus myosuroides* (Huds.) were determined in the untreated control plots.

Changes in Weed Species Frequencies, *A. myosuroides* Abundance and Herbicide Use

Weed species frequencies in the years before 1991 were not consistently reported. In some cases only the taxa were reported. Weed frequency was defined in this study as the percentage of the total number of field trials per year in which the species was recorded. Weed recordings for a total of 339 field trials from 1991 to 2011 were used to calculate the probability of occurrence per year and weed/taxa *i.e.* frequency. This trait was the dependent variable, whereas year was the explanatory variable. Generalized linear regression using the GLIMMIX procedure in SAS (version 9.3, SAS Institute, Cary, USA), assuming a binomial distribution of the residuals was carried out. We used the identity-link function and accounted for overdispersion. If the year slope was not significant ($P > 0.05$), it was dropped from the model. If the model did not converge average frequency and standard deviation thereof was reported.

Number of *A. myosuroides* heads per m² was used as measure of abundance to determine whether density changed over time (1972–2011). For this analysis, 223 trials were available in winter wheat and 175 in winter barley. Number of heads per m² was the dependent variable; year was the explanatory regression variable. Due to non-normality of the trait within year, the median was calculated and linear regression was employed for winter wheat and winter barley, separately using the MIXED procedure in SAS; number of trials per year was used as a weight. If the year slope was not significant, it was dropped from the model.

The assessed herbicide mixtures in the experiments were assumed to reflect the current herbicide strategies of farmers in south-western Germany in the corresponding years. Tested active ingredients (AIs) were aggregated per year to track changes of the used AIs and HRAC groups (Herbicide Resistance Action Committee 2014) over time. From 1987 to 1996 no comparable trials had been carried out.

Estimation of Yield Loss Functions

Yield loss curves were derived using data of 67 winter wheat trials (268 observations) and 55 winter barley trials (220 observations) from 1999 to 2011. If weed and crop coverage were determined in spring and yield data were available for all blocks at an individual site, data was included in the yield loss dataset. Weed and crop coverage were determined in spring: For winter barley, when between two and seven tillers were detectable (BBCH 25–27) and for winter wheat between one detectable tiller and early stem elongation (BBCH 21–32) (Zadoks et al. 1974). Weed infestation and crop status assessed in spring were used for weed-yield modelling, because Fritzsche et al. (2012) found a higher correlation between yields and weed coverage measured in spring than measured in autumn. Assessed variables were weed and crop coverage, yield in the untreated plots and the herbicide treatment with the highest average yield within the trial. To calculate yield loss, the weed-free yield per block within each trial was estimated. The herbicide treatment with the highest yield approximated the weed-free yield, assuming effective weed control and insignificant herbicide stress on the crop. The yield loss was calculated in each block according to Eq. 1:

$$yieldloss_{ijk} = 100 \cdot (1 - r_{ijk}) \quad (1)$$

where indices i, j and k code for year, site and block, $yieldloss_{ijk}$ is the yield loss in year i at site j in block k in percentage and relative yield (r) is calculated accordingly (Eq. 2):

$$r_{ijk} = \frac{yield_c_{ijk}}{yield_h_{ijk}} \quad (2)$$

where r is the ratio of the yield in year i at site j in block k of the untreated control ($yield_c$) and the yield in year i at site j in block k of the herbicide treatment with the highest average yield ($yield_h$).

A linear mixed model (Eq. 3) was employed for the winter wheat and winter barley datasets independently.

$$yieldloss_{ijk} = \alpha \cdot n_{ij} + \beta \cdot w_{ijk} + \gamma_i \cdot w_{ijk} + \gamma_i / s_j + e_{ijk} \quad (3)$$

Where $yieldloss$ is the dependant variable in year i at site j and block k , calculated according to Eqs. (1) and (2). α is the

regression coefficient for n , which is the number of herbicide treatments in year i at site j . Higher yield was expected to be observed where more herbicide treatments existed in a trial (sampling theory). Thus, n was included in the model as a co-variable. β is the regression coefficient for weed pressure w in year i , at site j in block k . y_i is the yearspecific regression coefficient for weed pressure. Weed pressure w_{ijk} was determined as: (i) absolute weed coverage (w_{abs}), (ii) relative weed coverage ($w_{w/t}$), which is weed coverage relative to total plant coverage and (iii) weed coverage relative to crop coverage ($w_{w/c}$). s_j is a random site effect nested in the random year effect y_i and e is the residual. The model (Eq. 3) was run independently with the variables w_{abs} , $w_{w/t}$ and $w_{w/c}$ as a measure of weed pressure w . Regression coefficients were estimated and for weed pressure (w) 95% confidence limits (95%-CL) were calculated for all three weed variables. The relative leaf area strongly correlates with the relative leaf cover (*i.e.* $w_{w/t}$) at early crop stages is reported to be a good predictor for yield loss relationships (Kropff and Spitters 1991; Ali et al. 2013). However, ratios of two coverage values are difficult to estimate. Thus, cross-validation ‘leaving one out’ was employed to determine which variable of w_{abs} , $w_{w/t}$ and $w_{w/c}$ was the best suited dependent variable for the weed yield loss relationship in these datasets (Hastie et al. 2009): The variable with the highest correlation coefficient (Pearson product-moment) between determined yield loss and predicted yield loss values was used for further ET analyses. The MIXED and CORR procedure in SAS (version 9.3, SAS Institute, Cary, USA) were used for analyses.

Calculation of ETs for Common Herbicide Mixtures

When w_{abs} , $w_{w/t}$ or $w_{w/c}$ is determined in the field, the yield loss can be predicted. Alternatively, ETs can be calculated. Because these variables do not distinguish between different weed species, ETs were determined for two frequently used herbicide mixtures being effective against the most common weeds in south-western Germany. Herbicide mixture I for winter wheat was: 9 g ha⁻¹ mesosulfuron-methyl, 1.8 g ha⁻¹ iodosulfuron-methyl-natrium and 27 g ha⁻¹ mefenpyr-diethyl (safener) (300 g ha⁻¹ Atlantis WG, BAYER), 144 g ha⁻¹ fluroxypyr (0.8 l ha⁻¹ Tomigan EC, Feinchemie Schwabda) and 15 g ha⁻¹ tribenuron-methyl (30 g ha⁻¹ Pointer WG, DuPont). Herbicide mixture II for winter wheat was: 13.7 g ha⁻¹ pyroxsulam, 4.6 g ha⁻¹ florasulam and 13.7 g ha⁻¹ cloquintocet-mexyl (safener) (0.2 kg ha⁻¹ Broadway WG, Dow AgroSciences). Herbicide mixture I in winter barley was the same as herbicide mixture I for winter wheat, except Atlantis OD was replaced with 1.2 l ha⁻¹ Axial 50 EC, Syngenta: 60 g ha⁻¹ pinoxaden, 15 g ha⁻¹ chloquintocet-mexyl (safener). For herbicide mixture II, Axial 50 was replaced by 2 l ha⁻¹ Arelon top SC, BAYER: 1 kg ha⁻¹ isoproturon. ETs for the herbicide

mixtures were calculated using Eq. 4 (Coble and Mortensen 1992).

$$ET = 100 \cdot \frac{(c_h + c_a)}{p_c \cdot \beta \cdot y_e} \quad (4)$$

Where herbicide costs (c_h) and application costs (c_a) were obtained from a regional machinery ring and a German herbicide retailer. Product prices (p_c) of 154 € t⁻¹ for winter barley and 176 € t⁻¹ winter wheat, average producer price 2006–2011 plus 10.7% value added tax, were taken for calculations (Anonymous 2014b). The yield effect of weed coverage (β) was taken from the analyses described above (Eq. 3) assuming full herbicide efficacy. Since the effect of weeds is determined as yield loss (%), an expected weed-free yield (y_e) needs to be estimated. For ET calculations, the average yield of the highest yielding herbicide treatments were taken from the yield loss data sets for both crops. Complementary, the lower and upper 95%-CL of the general weed regression coefficient (β) was used for ETs calculation. The ET based on the upper 95%-CL of β can be seen as risk adverse threshold; only in 2.5% of cases the regression term of the weed effect is expected to be higher than the estimate. The ET based on the lower 95%-CL of β can be seen as threshold for a risk taking approach, whereas the ET based on the estimate of β might be considered as rational approach.

Yield Trends

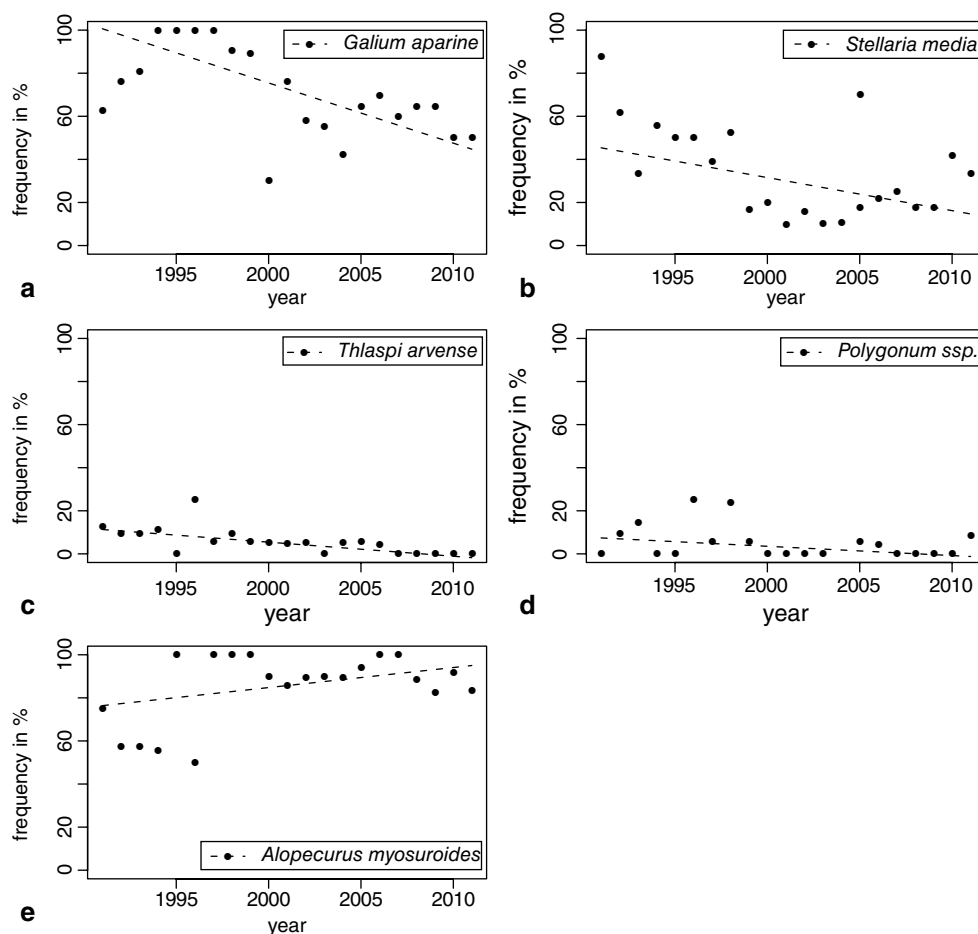
For the estimation of yield trends, yield from the untreated control and the highest yielding herbicide treatment of the trials carried out in different fields at Hohenheim (48°42′42″N, 9°12′41″E), were used to avoid variation. Trials were within a range of about 6 km. Data from 1992 to 2009 and from 1984 to 2009 were available for winter wheat and winter barley, respectively. Standard linear regression was employed in R (R Core Team 2012, stats package); yield was the dependent variable and year the independent variable. It was assumed that potential changes in farming practices occurring during the observation period affected both, the control and the herbicide treatment, similarly.

Results

Changes in Weed Species Frequencies

In winter cereals, about 40 weed species of 15 different families were observed (Table 1; Fig. 1). The majority were annual, broadleaved weeds. The main weeds were *Galium aparine* L. and *A. myosuroides*, which were observed in nearly 71 and 85% of the trials, respectively. *G. aparine* decreased significantly in frequency by 2.8%

Fig. 1 Species or genera for which a significant change in frequency could be determined in winter cereals carried out between 1991 and 2011: *Galium aparine* (a), *Stellaria media* (b), *Thlaspi arvense* (c), *Polygonum spp.* (d), *Alopecurus myosuroides* (e)



per year, whereas *A. myosuroides* increased by 0.9% per year (Fig. 1a and e). *Stellaria media* (L.) VILL. decreased by 1.5% per year (Fig. 1b). *Lamium purpureum* L. and *Matricaria chamomilla* L. frequencies ranged between 21 and 25%, respectively. Among *Veronica* genera, *V. persica* POIR., *V. agrestis* L., *V. hederifolia* L. and *V. arvensis* L. were recorded, the former being the most frequent. *Viola arvensis* MURRAY was observed on average in 15% of the trials per year. *Thlaspi arvense* L. and *Polygonum spp.* frequency significantly declined over time by 0.7% and 0.4% per year, respectively (Fig. 1c and d). *Polygonum spp.* declined almost completely due to decrease of *P. convolvulus* L., whereas *P. persicaria* L. and *P. aviculare* L. frequency remained constant at an average frequency of 0.9 and 0.7%, respectively.

Observed perennials were *Cirsium arvense* L. (SCOP.), *Sonchus arvensis* L., *Convolvulus arvensis* L. and *Rumex spp.* As volunteer only *Brassica napus* L. was observed. The grass weeds *A. myosuroides*, *Apera spica-venti* (L.) P. BEAUV., *Lolium spp.*, *Bromus spp.*, *Avena fatua* L. and *Poa annua* L. were recorded in the trials.

The number of *A. myosuroides* heads m^{-2} was highly variable over years and within years (Fig. 2). Linear regression did not indicate any significant change in the median num-

ber of heads during the last 40 years neither for winter wheat ($P=0.64$) nor winter barley ($P=0.56$). However, infestation rates were relatively high. Median number of heads was 336 per m^{-2} in winter wheat and 269 per m^{-2} in winter barley.

Use of Active Ingredients

The number of AIs applied in the experiments increased over time (Table 2) and shares of the HRAC group changed considerably. Before the 1990s, used AIs belonged to the group C, K, M and O. Since 1997, AIs of the ACCase inhibitors (A) and of the ALS-inhibitors (B) were integral parts. AIs of the group C1 and M were not further tested in the experiments or were not anymore registered for use. Among the PS-II inhibitors (C), only isoproturon was of relevance over the whole period of time. Flufenacet (K3) and pendimethalin (K1) were permanently part of the experiments since 1997.

Yield Loss Curves

The year-specific weed effect was not significant for none of the weed variables neither for winter wheat nor for winter barley and was dropped from the model. The co-variable

Table 1 Modelled annual frequencies and their standard error (*SE*) of weed species for which analyses did not indicate a significant change over time (1991–2011). Average frequency and standard deviation (*SD*) are reported if model did not converge

Weed species	Estimated frequency	SE/SD
Veronica spp.	33.0	3.2
<i>Veronica persica</i>	16.2	3.6
<i>Veronica hederifolia</i>	14.8	0.6
<i>Veronica agrestis</i>	2.4	0.9
<i>Veronica arvensis</i> ^a	0.3	1.2
<i>Lamium purpureum</i>	21.5	3.0
<i>Matricaria chamomilla</i>	24.8	3.2
<i>Viola arvensis</i>	14.8	1.8
<i>Capsella bursa-pastoris</i>	5.6	1.5
<i>Myosotis arvensis</i>	5.0	1.4
<i>Apera spica-venti</i>	6.2	1.0
<i>Geranium dissectum</i> ^a	4.5	4.8
<i>Fumaria officinalis</i>	3.2	1.1
Bromus spp.	4.1	1.3
<i>Brassica napus</i>	3.5	1.2
<i>Poa annua</i>	1.8	0.9
Galeopsis spp.	2.7	1.1
<i>Lapsana communis</i>	2.4	0.8
<i>Papaver rhoeas</i>	1.8	0.7
<i>Sinapis arvensis</i> ^a	1.2	2.6
<i>Cirsium arvense</i>	1.2	0.7
<i>Anthemis arvensis</i> ^a	1.0	2.0
Amaranthus spp.	1.2	0.7
<i>Avena fatua</i>	0.9	0.6
<i>Polygonum persicaria</i>	0.9	0.4
<i>Chenopodium album</i>	0.6	0.5
Lolium spp.	0.9	0.4
<i>Aethusa cynapium</i>	0.9	0.4
<i>Helianthus annuus</i>	0.6	0.4
<i>Polygonum aviculare</i> ^a	0.7	2.1
Rumex spp. ^a	0.2	1.0
<i>Centaurea cyanus</i> ^a	0.2	1.0
<i>Convolvulus arvensis</i>	0.3	0.3
<i>Sonchus arvensis</i>	0.3	0.6

^aAverage frequency and standard deviation displayed

number of herbicide treatments and the weed pressure effect had a significant effect on yield loss in all three models run and in both crops (Table 3). For winter barley, the regression coefficients were generally higher compared with winter wheat. Cross-validation indicated that the three measures of weed pressure were almost equally well suited to predict yield loss in both crops. Correlation coefficients for winter barley were 0.860, 0.860 and 0.852 for w_{abs} , $w_{w/t}$ and $w_{w/c}$ respectively. For winter wheat, correlation coefficients were 0.891, 0.893, 0.888 for w_{abs} , $w_{w/t}$ and $w_{w/c}$.

Economic Thresholds

In winter wheat, risk adverse thresholds *i.e.* using the upper 95 %-CL estimate of the weed yield regression coefficient

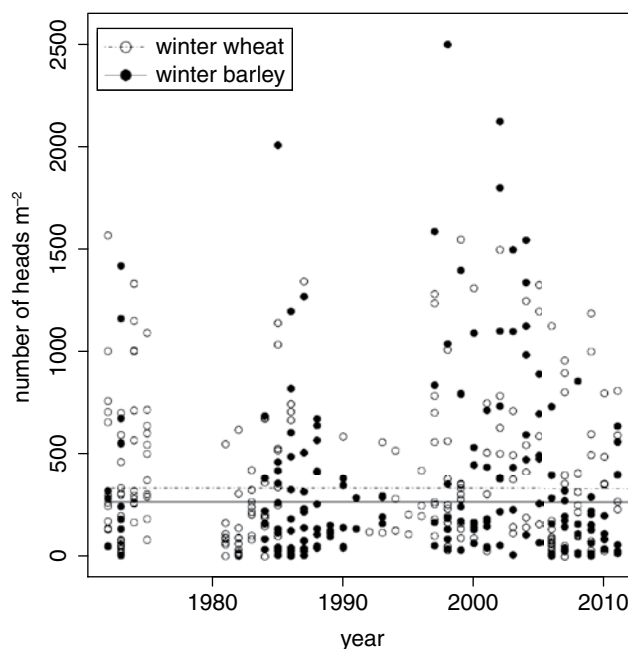


Fig. 2 Counted *Alopecurus myosuroides* heads in trials carried out in winter wheat ($n=223$) and winter barley ($n=175$) between 1972 and 2011; median number of heads in the trials is indicated with a line (winter barley) and with dashed line (winter wheat)

were 9.8% absolute weed coverage for herbicide mixture I and 9.2% for herbicide mixture II. In winter barley conservative thresholds were 8.9% weed coverage for herbicide mixture I and 4.5% for herbicide mixture II (Table 3).

Yield Trends

In winter wheat, there was a trend of an annual yield increase of about $0.16 \text{ t ha}^{-1} \text{ a}^{-1}$ ($P=0.0019$), when weeds were controlled by herbicides (Fig. 3a). No significant yield change ($P=0.73$) was found over the years in the untreated control, in which yield was about 7.4 t ha^{-1} on average. Minimum and maximum yield observed in the untreated control over 18 years were: 5.5 and 9.5 t ha^{-1} , respectively. In winter barley, there was an annual yield increase in the highest yielding herbicide treatment of about 0.08 t ha^{-1} ($P=0.008$), resulting considerably smaller compared with winter wheat (Fig. 3b). With weed competition no significant change was found ($P=0.75$) and average yield level was about 6.7 t ha^{-1} . Minimum yield was 4.6 t ha^{-1} , while maximum yield was 8.8 t ha^{-1} in the untreated control.

Table 2 Active ingredients (AIs) with HRAC code (herbicide resistance action committee (<http://www.hracglobal.com/>), employed in the herbicide treatment levels of the winter cereals trial programmes from 1981 to 2011. From 1987 to 1996 no comparable trials were carried out

HRAC code	AI	81	82	83	84	85	86 ^a	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	
A	Fenoxaprop-P							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
	Clodinafop							x	x		x	x	x	x	x	x	x	x	x	x	x	x	
	Pinoxaden															x	x	x	x	x	x	x	
B	Metsulfuron						x				x	x	x	x	x	x	x	x	x	x	x	x	
	Thifensulfuron							x	x	x	x	x	x					x	x				
	Amidosulfuron							x	x	x	x	x	x	x	x	x	x	x	x	x			
	Flupyr-sulfuron								x	x	x	x	x	x	x	x	x	x	x	x	x	x	
	Tribenuron										x	x	x	x	x	x	x	x	x	x	x	x	
	Iodosulfuron										x	x	x	x	x	x	x	x	x	x	x	x	
	Mesosulfuron											x	x	x	x	x	x	x	x	x	x	x	
	Sulfosulfuron											x	x	x									
	Tritosulfuron												x	x	x	x	x	x	x	x			
	Triasulfuron																x	x	x				
	Pyroxsulam																			x	x	x	x
	Florasulam										x	x	x	x	x	x	x	x	x	x	x	x	x
	Penoxsulam																				x	x	x
	Propoxycarbazone										x	x	x	x	x	x	x	x	x	x	x	x	x
	C1	Cyanazine				x	x	x															
C2	Methabenzthiazuron	x	x	x																			
	Linuron	x			x																		
	Isoproturon	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
	Chlortoluron	x															x	x	x	x	x	x	
C3	Bentazone	x	x	x	x	x	x																
	Ioxynil	x	x	x	x	x	x					x	x	x	x								
	Bromoxynil	x	x	x	x	x	x									x							
E	Fluoroglycofen							x	x	x													
	Bifenox															x							
	Carfentrazone								x	x	x	x	x	x	x	x	x	x	x				
	Flumioxazin															x	x	x	x	x	x	x	
	Cinidonethyl																					x	
F1	Diflufenican							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
	Picolinafen										x	x	x	x	x	x	x	x	x	x	x	x	
	Flurtamone							x	x	x	x		x	x	x	x	x	x	x	x	x	x	
	Beflubutamid											x		x	x	x	x	x	x	x	x	x	
K1	Trifluralin	x			x											x							
	Pendimethalin	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
K3	Flufenacet						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
M	Dinoseb acetate	x	x		x	x	x																
	Dinoterb	x	x	x	x	x	x																
N	Prosulfocarb										x	x	x	x	x	x	x	x	x	x	x	x	
O	Dichlorprop	x	x	x	x	x	x																
	Mecoprop-P	x	x	x	x	x	x					x		x	x	x	x	x	x				
	MCPA					x	x																
	Fluroxypyr							x	x	x			x	x	x	x	x	x	x	x	x	x	
	Dicamba																x						

^aFrom 1987 to 1996 no comparable trials were carried out

Discussion

Changes in Weeds and Herbicide Use

Weed frequencies were rather stable over the last two decades in both winter cereal crops. Observed weeds were

generally nitrophilic species (Ellenberg 1991) with a strong association to winter annual crops. Major changes in weed community might have already occurred in the 1950s and 1960s when species intolerant to application of fertilizers disappeared (Robinson and Sutherland 2002). Andreassen and Streibig (2011) reported a relatively strong decline in

Table 3 Yield loss model estimates for absolute weed coverage (w_{abs}), relative weed coverage to total plant coverage ($w_{w/t}$) and for weed coverage relative to crop coverage ($w_{w/c}$) for winter wheat and winter barley. n is the number of herbicide treatments included as co-variable in the model. Economic thresholds were calculated based on the upper 95%-CL for a risk adverse attitude, based on the estimate for a rational attitude and based on the lower 95%-CL for a risk taking attitude. ETs were calculated for 2 herbicide mixtures

Yield loss model				Economic threshold							
Model	Regression		95%-CL		Herbicide mixture I ^a			Herbicide mixture II ^b			
	Estimate	<i>P</i> -value	Lower	Upper	Risk adverse	Rational	Risk taking	Risk adverse	Rational	Risk taking	
Winter wheat											
M1	w_{abs}	0.49	<0.0001	0.34	0.64	9.8	12.8	18.4	9.2	12.1	17.4
	n	1.89	<0.0001								
M2	$w_{w/t}$	0.48	<0.0001	0.34	0.62	10.0	13.0	18.4	9.4	12.2	17.4
	n	1.63	<0.0001								
M3	$w_{w/c}$	0.16	<0.0001	0.11	0.21	29.2	38.8	57.8	27.6	36.6	54.7
	n	2.27	<0.0001								
Winter barley											
M1	w_{abs}	0.67	<0.0001	0.47	0.87	8.9	11.5	16.4	4.5	5.9	8.3
	n	1.48	<0.0001								
M2	$w_{w/t}$	0.64	<0.0001	0.46	0.84	9.2	12.0	16.8	4.7	6.1	8.6
	n	1.29	0.0007								
M3	$w_{w/c}$	0.20	<0.0001	0.13	0.27	28.9	38.7	58.8	14.7	19.7	29.9
	n	2.11	<0.0001								

^aFor winter wheat: 9 g ha⁻¹ mesosulfuron-methyl, 1.8 g ha⁻¹ iodosulfuron-methyl-natrium and 27 g ha⁻¹ mefenpyr-diethyl (safener), 144 g ha⁻¹ fluroxypyr and 15 g ha⁻¹ tribenuron-methyl. For winter barley: 60 g ha⁻¹ pinoxaden, 15 g ha⁻¹ chloquintocet-mexyl (safener), 144 g ha⁻¹ fluroxypyr and 15 g ha⁻¹ tribenuron-methyl

^bFor winter wheat: 13.7 g ha⁻¹ pyroxsulam, 4.6 g ha⁻¹ florasulam and 13.7 g ha⁻¹ cloquintocet-mexyl (safener). For winter barley 1 kg ha⁻¹ isoproturon, 144 g ha⁻¹ fluroxypyr and 15 g ha⁻¹ tribenuron-methyl

weed abundance between 1960s and the 1980s and a more stable state between the 1980s and 2000s in Denmark. This might be ascribed to governmental policies requiring lower efficacy goals for herbicide applications. In contrast, Gerhards et al. (2013) found a distinct decline in weed species between the 1940s, the 1970s and 2011 in a county in south-western Germany. Meyer (2013) observed the same trend comparing data from the 1950s/1960s and 2009. These contrasting results might be due to the different time intervals compared and fields chosen for weed frequency determination. In our study weed frequency data was based on weed control experiments carried out in fields with representative weed infestation and thus very rare weeds were not likely to be observed.

Frequency of *A. myosuroides* increased significantly over time. However, head density did not increase during the 40 years of observation, neither in winter wheat nor in winter barley. Increase of *A. myosuroides* frequency can be ascribed to a high amount of winter cereals in the rotation, reduced soil tillage and the trend of machine pooling by which seeds are spread to other fields (Gehring et al. 2012a).

The recommended low ET for *G. aparine*, namely 0.1–0.5 plants m⁻² (Gerowitt and Heitefuss 1990) and the consequent control of this weed may have contributed to its decline in frequency. A Danish study showed a large decline in the seed banks of *S. media* in arable fields between 1964

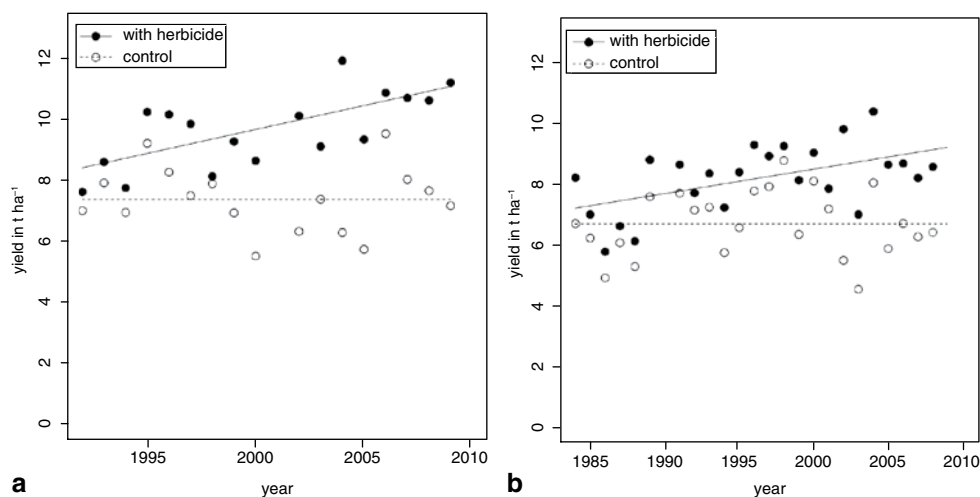
and 1989 (Jensen and Kjellsson 1995 in Robinson and Sutherland 2002). The declining weed frequencies of *G. aparine* and *S. media* in our study may be due to highly effective herbicides, in combination with precisely and optimally timed nitrogen fertilization, which resulted in vigorous and competitive crop stands (Meyer 2013).

The pronounced use of ALS-inhibitors during the experiments and in farmers' fields, might lead to resistance problems (Gehring et al. 2012a). Herbicide resistance could cause weed frequency shifts and increases in infestation levels soon. Thus, it could become the next cause of weed community changes in winter cereals after the relatively stable last two decades in south-western Germany. Sound resistance management strategies are crucial. Flufenacet (K3), prosulfocarb (N) and the group F1 are considered important components for resistance management in winter cereals (Gehring et al. 2012b). These groups were common components in the trials since the late 1990s.

Estimation of Weed Effects on Yield and Economic Thresholds

Several studies reported relative leaf area of weeds or relative weed coverage to be good predictors for yield or yield loss (Kropf and Spitters 1991; Ali et al. 2013). In the present study absolute coverage, relative weed coverage and rela-

Fig. 3 Yield of the untreated control and the highest yielding herbicide treatment level in winter wheat trials (1992–2011) (a) and winter barley trials (1984–2011) (b) at the site Hohenheim, Germany



tive weed to crop coverage explained yield loss in the data sets almost equally well. One disadvantage of weed coverage assessments compared with weed density assessments is that the effect of grass weeds such as *A. myosuroides* may be underestimated due to their erectophile leaf morphology and thus small coverage but high damage potential. The ETs found for absolute weed coverage assuming risk aversion were similar to the ETs of 5 to 10% coverage tested by Gerowitt and Heitefuss (1990) for dicotyledonous weeds. This indicates that despite the considerable changes observed during the last decades in agricultural systems these values are still appropriate to be used by farmers.

Farmers in south-western Germany commonly spray herbicides in autumn to control annual broad-leaved and annual grass weeds in early sown (late September to early October) winter wheat and winter barley. In spring, farmers are often uncertain whether another herbicide application is needed. The derived thresholds in this study provide a simple decision aid for farmers in this situation.

Yield Trends and the Need for Effective Weed Control

In the present study, yield increase without weed competition was higher than yield increase reported in the literature for winter barley and higher for winter wheat in Germany (Hartmann 2008; Ahlemeyer et al. 2008). This might be ascribed to the site Hohenheim, which is suited for winter cereal production, whereas the other reported yield increases were averages taken from many sites. In contrast, no annual yield increase could be found if weeds interfered with the crop. Neither any occurring progress in agrotechnology, nor any genetic yield gain could become evident in the fields without effective weed control either in winter wheat or winter barley. This clearly emphasizes how crucial effective weed control is, to guarantee yield and that farmers can profit from breeding progress and other technological advances. Apart from alternating and combining herbicides

a more integrated approach, combining measures such as rotation of summer and winter annual crops, mechanical control measures, intensive tillage operation including inversion tillage, stubble tillage, cover crops, intercropping and delayed sowing should be campaigned to keep available herbicides effective (Melander 1995; den Hollander et al. 2007; Gehring et al. 2012a; Brust and Gerhards 2012).

Acknowledgements We thank the institutions and the many people involved in the ‘Gemeinschaftsversuche Baden-Württemberg’ during the last four decades and special thanks to Cathrin Reichert for technical support.

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