Modelling the Effects of a Ban of Glyphosate on Weed Management Strategies in Maize Production

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Abstract

A bio-economic model is developed that allows a detailed representation of optimal weed management decisions. Focussing on German maize production, we apply the model to the effects of a glyphosate ban on farmers' income, other herbicide use, maize yields and labour demand. We find that a glyphosate ban has only small income effects. Moreover, our results show that selective herbicides are not used at higher levels, but glyphosate is rather substituted by mechanical practices leading to higher labour demand. Slight yield reduction due to less intensive pre-sowing strategies turns out as more profitable than maintaining current yield levels.

Keywords: output damage control, herbicide, maize, glyphosate, Germany

1 Introduction

Reducing risks caused by pesticide application is high on the European agri-environmental policy debate. Different measures are proposed to control pesticide use in order to yield more sustainable agricultural systems such as banning specific pesticides (e.g. glyphosate; Schulte and Theuvsen, 2015) or introducing pesticide taxes (Böcker and Finger, 2016; Finger *et al.,* 2017). Especially the renewed licensing or banning of the broad-spectrum herbicide glyphosate provoked heated discussions after the IARC classified glyphosate at "probably carcinogenic to humans" (Guyton *et al.*, 2015). *Ex-ante* information of such policy measures on risk reduction to humans and the environment as well as impacts on farmer's income are needed to inform the policy debate (Falconer, 1998). As substitution effects with other herbicides are likely if specific products are targeted, potential changes in farm management must be depicted in detail. In this paper, we develop a tool for such detailed impact assessment of environmental standards or other policy measures affecting specific pesticides and apply it to assess a potential ban of glyphosate.

In available assessments, mainly positive and normative modelling approaches are applied (Böcker and Finger, 2017). Positive approaches primarily use econometric methods based on historical data, for instance of pesticide applications. Normative models presume optimal decision making based on more or less detailed production function approaches combined with an economic objective such as profit maximisation. They can hence be used for what-if-analyses even if observations are missing. Existing normative approaches are, however, not detailed enough to assess measures addressing individual pesticides, such as glyphosate in our application. For example, Guan *et al.* (2005) work with a monetary aggregate over fungicides, herbicides and other pesticides; however, higher total costs for pesticide applications do not necessarily lead to a better weed treatment and vice versa. Kuosmanen *et al.* (2006) use the amount of active substances (AS) of insecticides as an indicator for pesticide use in cotton. Karagiannis and Tzouvelekas (2012) measure insecticide application in olive orchards based on litres of insecticides, but ignoring the diversity of different products.

In this paper, we extend the existing literature by making use of the output damage function approach (e.g. Karagiannis and Tzouvelekas 2012), differentiating in detail a larger set of pre-sowing and post-sowing weed control options with regard to their yield impact. Specifically, we consider for each strategy both costs and effectiveness of controlling individual weeds. Moreover, we develop a framework that is site-specific and allows investigating weed management over time and space. Our empirical analysis focusses on silage maize, one of the most relevant crops in Germany, where pest management mainly relies on herbicide application (JKI, 2016). We apply the model to the Federal State of North-Rhine-Westphalia (NRW), Germany, by accounting for the specific weed pressure and yield potential at municipality level. The model identifies economically optimal herbicide strategies in silage maize in each municipality at given pesticide and crop prices and environmental standards. In our empirical application, we analyse the impact of a ban of glyphosate on herbicide use and/or mechanical weed control measures and related costs compared to the current situation. Currently, no alternative chemical herbicide strategies are approved to replace glyphosate for pre-sowing application (Kehlenbeck *et al.*, 2015) such that mechanical weed control is the only alternative which removes all potential risks from herbicides before sowing. However, after sowing, alternative herbicides could potentially be used at higher rates, even increasing the overall risk.

2 Methodology

We develop a bio-economic weed control model for silage maize in *m* municipalities in NRW. A two-year cropping period is considered where maize is grown in each of the two years *t*, a standard farming practise. The expected gross margin $E(\pi)$ in year *t* for different pre- (index *b*) and post-sowing (index *h*) weed control strategies is defined as:

$$E(\pi_{m,t,b,h}) = [y^*_{m,t,b,h} \cdot E(p) - c_b(b_{i,m,t}) - c_s(b_{i,m,t}) - c_h(h_{i,m,t}) - c_f(y) - c_o], \quad (1)$$

where $y^*_{m,t,b,h}$ is the expected yield, $E(p)$ is the expected price for maize, $c_b(b_{i,m,t})$ and $c_h(h_{i,m,t})$ are the pre- and post-sowing weed management (and tillage) costs for a certain strategy, $c_s(b_{i,m,t})$ are variable costs for sowing depending on the pre-sowing strategy (the more expensive direct precision drill is needed for conservation tillage), $c_f(y)$ are costs for fertiliser depending on the yield and c_o are other costs (proportionate costs for rating and liming). Harvest costs are not included because maize is sold ex field such that the buyer performs the harvest which is reflected in the price.

2.1 The damage control approach

An output damage function is used to determine the expected yield y^* (Pannell, 1990; Fox and Weersink, 1995). It depicts first the effect of the damage control input on the population of the damaging organism and from there the resulting yield reduction (Karagiannis and Tzouvelekas, 2012:419). We follow here the more standardised notation of Guan *et al.* (2005). The concept is based on a distinction in the production function $y=G(x,D(z))$ between productive (x) and damage-controlling inputs (z) where $D(z)$ is the damage controlling effect on the interval [0,1]. If $D(z)$ is equal to unity, no losses due to pests, diseases or weeds occur. Besides chemical inputs, also mechanical inputs such as hoeing or ploughing can be considered as damage-controlling which challenges a clear distinction between z and x. The classical form of $D(z)$ is either exponential, logistic or of the Weibull form (Lichtenberg and Zilberman, 1986). We follow Guan *et al.* (2005) and use the exponential form which represents well the underlying biological processes:

$$D = 1 - e^{-(\beta_0+\beta_1\cdot z)^2}, \quad \beta_0, \beta_1 \geq 0. \quad (2)$$

The functional form implies decreasing marginal damage control in input use, a reasonable assumption as, e.g., additional weed control on an almost weed free field will not lead to much higher damage control. The parameters β_0 and β_1 have to be assessed (see next sections) and z is chosen level of damage control as the decision variable.

2.2 Specification of the damage controlling effect

We consider 32 different weeds in our analysis. Each plant protection strategy is characterised by its weed specific damage control effect, i.e. a column vector *h* with *j 1 x 32* entries ranging between 0 and 1, since specific herbicides and mechanical strategies differ in their impact on individual weeds. Often, an herbicide strategy comprises several products. The resulting control success is typically not additive since the comprised herbicides may have a similar spectrum of action. More likely is the case that the maximum suppression effect of any herbicide is crucial for the success. We add a multiplier a_i to each weed $w_{m,i}$ to differentiate yield depression effects by weed, depicted by the average abundance (a_i) which measures the affected area share when that weed occurs. Finally, in order to quantify the site-specific damage controlling effect of specific herbicides, a weed-row vector

w with size i 32×1 depicts for each municipality m the probability that a weed occurs. The three vectors– probability of weed occurrence w, affected share a, and damage control for each weed h – define jointly the control success z for each herbicide strategy j in the different municipalities m:

$$z_{m,j} = \sum_{i}^{32} w_{m,i} \cdot a_i \cdot h_{j,i} \,. \tag{3}$$

Eq. (3) presents the post-sowing weed controlling effects. In a similar manner, a vector $v_{m,j}$ can be constructed that accounts for pre-sowing weed management effects (denoted as b_i):

$$v_{m,j} = \sum_{i}^{32} w_{m,i} \cdot a_i \cdot b_{j,i} \,. \tag{4}$$

2.3 Choice of functional form and implementing the damage controlling effect

Inserting the damage control success expression from (3) in (2) yields the following specification:

$$D = 1 - e^{-(\beta_0 + \beta_1 \cdot \sum_i^{32} w_{m,i} \cdot a_i \cdot h_{j,i})^2}, \quad \beta_0, \beta_1 \geq 0. \tag{5}$$

One of the remaining issues is to determine the form of the production function. We follow Swinton and King (1994) as well as Bosnić and Swanton (1997) and use the rectangular hyperbolic approach of Cousens (1985), which allows accounting for biological effects such as time of emergence. Thus, the yield function dependent on weed control success D (0=no weed) is defined as follows:

$$y^*_{m,t,b,h} = y^a_{m,t} \cdot \left[1 - I \cdot \frac{D}{100 \cdot \left(e^{C \cdot T} + I \cdot \frac{D}{A} \right)} \right]. \tag{6}$$

y_a is the attainable yield when no weeds are present, I is the percent yield loss as D approaches 0 (i.e. D is not yet 0), A is the percent yield loss as D approaches infinity, T is the time of weed emergence in relation to the crop emergence (in growing degree days with a baseline of 10°C per day) and C is the rate at which the yield loss I decreases as T becomes larger. Fungi and insects are of limited relevance in German maize production or can be controlled by seed dressing or resistant varieties such that except for herbicides usually no other pesticides are applied (JKI, 2016). Thus, the attainable yield y^a is defined as the potential yield under given climatic and soil conditions, i.e. under no nutrient stress. Nevertheless, using yield term (6) neglects pre-sowing weed controlling practices depicted by $v_{m,j}$. Accounting for that, the expected yield y^* for a specific strategy becomes:

$$y^*_{m,t,b,h} = \underbrace{\left(1 - e^{-(\alpha_0 + \alpha_1 \cdot v_{m,j})^2}\right)}_{\text{Pre-sowing}} \cdot y^a_{m,t} \cdot \underbrace{\left[1 - I \cdot \frac{e^{-(\beta_0 + \beta_1 \cdot z_{m,j})^2}}{100 \cdot \left(e^{C \cdot T} + I \cdot \frac{e^{-(\beta_0 + \beta_1 \cdot z_{m,j})^2}}{A} \right)} \right]}_{\text{Post-sowing}}. \tag{7}$$

2.4 Parameterisation and pesticide application restrictions

In order to calibrate the model and to parameterise the production function, we conducted expert interviews with the senior herbicide consultant and three regional herbicide consultants of the chamber of agriculture from NRW who identified most frequently used strategies in different regions of NRW depending on soil types.[1] Furthermore, we collected data on the observed yield $\bar{y}$ in each municipality m which should reflect the current weed control practise (Information und Technik Nord-

[1] Regarding herbicide strategies, three major soil types can be distinguished in NRW: sandy soils where herbicides against *Panicoideae*-varieties are applied. On clayey soils, strategies against *Alopecurus myosuroides* are preferred, whereas on good loamy soils, simple and cheap strategies are used. For each soil type, two matching municipalities were selected yielding six municipalities where current weed control strategies are known. Municipalities where a mix of soil types is observed accordingly also apply a mix of strategies.

rhein-Westfalen, 2016). In order to estimate the parameters of interest (α_0, α_1, β_0 and β_1), we determine the parameter values which minimise the error term between the observed yields and the yield simulated with the observed control strategies in selected municipalities representative for the three soil types (municipalities which have homogeneous soil types but different potential yields):

$$\min \varepsilon = \sum_{m}^{6} y^{*}_{m,t^*,b^*,h^*} - \bar{y}_{m,t} \quad (8)$$

Thus, we can directly account for the nonlinearity of the production function. Some further details need to be reflected during estimation and simulation. Firstly, we assume that the strategy needs to be changed from year to year to avoid building up resistance against specific AS in the weed population. More specifically, we classified the strategies based on the Herbicide Resistance Action Committee (HRAC, 2005) into groups and added a constraint which prevents that strategies from the same groups are used in two consecutive years. Second, special requirements for nicosulfuron-containing strategies have to be included since this AS is only allowed to be applied every second year by law (code NG327 for the use of plant protection products) (eq. not shown).

Once the parameters are determined and inserted into the production function, optimal strategies can be determined for each m and t according to eq. (1), i.e. profits can be maximised for each municipality and year by choosing pre- and post-sowing shares for the control strategies:

$$E(\pi_{m,t}) = \sum_{b=1}^{24}\sum_{h=1}^{55} E(\pi_{m,t,b,h}) \cdot S_{b,m,t} \cdot \varphi_{b,glyphosate} \cdot S_{h,m,t}\,, \;\; S_{b,m,t}\ and\ S_{h,m,t} \in [0,1] \quad (9)$$

$$\max \pi = \sum_{m=1}^{377}\sum_{t=1}^{2} E(\pi_{m,t}). \quad (10)$$

φ is the information matrix whether glyphosate is allowed in the analysed scenarios. $S_{b,m,t}$ and $S_{h,m,t}$ are the shares of the selected control strategies of the farmers for pre- (b) and post-sowing (h) weed management and $E(\pi_{m,t,b,h})$ is the profit for each strategy which reflects the expected yield, related fertiliser and other costs including the costs for weed control.

The model is written in General Algebraic Modelling System (GAMS) code. We simulate optimal herbicide strategies under a baseline where glyphosate can be applied throughout the two periods and a counterfactual where glyphosate is banned. We conduct sensitivity analysis with regard to p and T, so that effects of higher or lower prices and higher or lower weed pressure can be seen. The latter is depicted by earlier or later maize emergence compared to weeds, e.g. $T=0$ means that maize and weeds emerge at the same time, $T=-50$ means that weeds emerge five 10°-days earlier. We test the following five hypotheses: H1) average post-sowing strategies change in case of a glyphosate ban, H2) costs for weed management increase in case of a glyphosate ban, H3) working force demand increases in case of a glyphosate ban, H4) the gross margin decreases in case of a glyphosate ban, and H5) yields significantly decrease in case of a glyphosate ban.[2]

3 Data

We focus on the most important weeds in maize cultivation for our case study region (defined as more than 10% degree of presence, following the samples of Mehrtens *et al.* (2005) and Mol *et al.* (2015). Additionally, *Digitaria ischaemum* and *Mercurialis annua* were included; weeds which are of importance in specific regions of NRW as they are also listed in the agricultural recommendations (see resulting list in Table 1). Information on the occurrence of weeds is taken from the 2.88x2.75km distribution raster of Germany's pteridophytes and flowering plants (NetPhyD and

[2] For the hypotheses, we use the average of the periods t_1 and t_2.

BfN, 2013), and mapped via GIS operations to municipality areas. We included only the 377 municipalities which reported maize cultivation in recent years. Each municipality receives weed specific occurrence probabilities which reflect the area weighted average of raster cells where each weed was observed (see data for *Alopecurus myosuroides* and *Setaria viridis* in Fig. 1). Information on the average abundance, i.e. the share of affected area when a weed is observed and not controlled, is used from long-term field trials (Table 1).

Table 1. Maize grass-weeds and weeds implemented in the output damage function approach

Name	Average abundance (%)	Name	Average abundance (%)
Grass-weeds:		*Fumaria officinalis*	2.0
Alopecurus myosuroides	21.3+	*Galinsoga parviflora*	12.0
Digitaria ischaemum	21.3+	*Galium aparine*	7.0
Echinochloa crus-galli	22.0	*Geranium pusillum*	6.0
Elymus repens/Elytrigia repens	21.3+	*Lamium spp.*	6.0
Poa annua, P. trivialis	2.0	*Matricaria spp.*	13.0
Setaria viridis	40.0	*Mercurialis annua*	6.8+
Broad-leaved weeds:		*Persicaria lapathifolia*	11.0
Amaranthus retroflexus	13.0	*Persicaria maculosa*	3.0
Atriplex patula	1.0	*Polygonum aviculare agg.*	3.0
Brassica napus	18.0	*Rumex obtusifolius*	4.0
Capsella bursa-pastoris	5.0	*Solanum nigrum*	3.0
Chenopodium spp.	20.0	*Sonchus spp.*	2.0
Cirsium arvense	4.0	*Stellaria media agg.*	6.0
Convolvulus arvensis	2.0	*Thlaspi arvense*	3.0
Equisetum arvense, E. palustre)	6.8+	*Veronica spp.*	2.0
Fallopia convolvulus	12.0	*Viola arvensis*	5.0

Note: Abundance-values marked with a + are estimates according to mean values of grass weeds or broad-leaved weeds. Data on year to year variation of the abundance were not found. *Brassica napus* was included for potential extensions of the model by crop rotations. Source: Meinlschmidt *et al.* (2008).

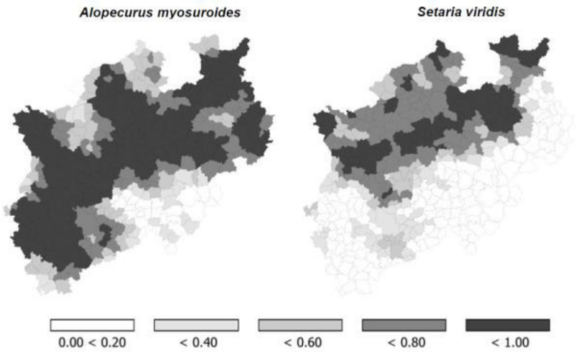

Fig. 1. Spread of *Alopecurus myosuroides* (left) and *Setaria viridis* (right).
Reference: NetPhyD and BfN (2013), data converted to municipality borders.

We consider those herbicides (combinations) that are recommended by the Chamber of Agriculture of North Rhine Westphalia (LWK NRW, 2015a) and the Bavarian State Research Centre for Agriculture (LfL, 2016). These recommendations are widely used in agricultural extension and also published in agricultural magazines. Because of lack of data how different doses affect weed control, we use the recommend dose in each strategy instead of trying to also solve for an optimal rate (Pannell, 1990). However, these doses may vary between strategies comprising the same AS. In total, 55 different post-sowing herbicide strategies were defined, where one reflects zero control, 6 are mechanical only and the remaining 48 apply herbicides once or twice. For each of those 55 strategies, data by the LfL (2016) and the LWK NRW (2015a) define the suppressing efficiency against each of the 32 weeds in the interval [0,1]. A value of 1 characterises total eradication, a value of zero indicates no impact on the weed, and a value between zero and one was assigned if part of the population is removed. Unfortunately, the data were not available for all 32 weeds in which case manufacturer information (obtained from product brochures) was used. Thereby, in general three categories are displayed: well or very well controllable, sufficiently controllable and not sufficiently controllable. For the first category, we assume an efficacy of 0.90, for the second category 0.33 and for the third category null efficacy.

To quantify the efficacy of the mechanical strategies, we combine information from extensive or organic farming systems with expert knowledge. Data on mechanical post-sowing techniques could be found in Kees (1984, unpub., cit. from Hoffmann, 1990). Additionally, we consulted the organic farming expert of the Chamber of Agriculture from Lower Saxony for information on the mechanical harrowing and hoeing frequency, and their effect on specific weeds. There are 24 different pre-sowing plant protection strategies in our model, consisting of mouldboard ploughing, different chisel plough and harrow combinations and glyphosate combinations. Except for glyphosate, no other herbicides are allowed before sowing (Kehlenbeck *et al.*, 2015). We could not find unambiguous data about the yield increasing or decreasing effect of different tillage systems. Therefore, with respect to the weed controlling capacity of conventional and conservation tillage, both strategies have almost the same yield potential. Conventional tillage has only slight advantages in weed control.

Data about actual yields are available at county-level (53 counties in NRW; IT NRW, 2016), and $\bar{y}$ is the five year average of the actually observed yield from 2011 and 2015. A 5% increase of the expected yield is assumed for the second year t_2. Oerke (2006) estimated a 5% yield loss from weeds in Western European maize production with usual weed control strategies ($y^a = 1.05\ \bar{y}$). For information about maximum losses under zero control (scalar A in eq. (7)), we draw on field trials by Söchting and Zwerger (2012). Maize yields with herbicide treatment were up to 63.8% higher compared to the untreated control group (A = 63.8%). For I and C in eq. (7), we rely on Bosnić and Swanton (1997), who estimated I = 0.3% and C = 0.017. Further restrictions of the estimation model are that the no-till pre-sowing strategy with no herbicide application has to achieve a yield level between 85% and 90% and that the ploughing strategy has to be larger than 95% (Gehring *et al.*, 2012). The zero control post-sowing strategy is fixed at 86% for normal weed emergence (in relation to the field trials of Söchting and Zwerger, 2012). Based on this data, the estimates from eq. 8 are as follows: ε has a value of ± 3.5% of $E(y)$. The best fit parameter values are $\alpha_0=1.307$, $\alpha_1=0.760$, $\beta_0=0.929$ and $\beta_1=0.223$ (estimated at $T=-20$).

Herbicide's costs are based on 2015 recommended retail prices from a German agricultural trader (Roth Agrarhandel, 2015). For labour costs, € 17.5/h are assumed. In our study region, organic fertiliser is no limiting production factor (see Gömann *et al.*, 2010 for details) so that we assume that slurry is for free. The most relevant cost parameters are presented in Table 2.

Table 2. Machinery costs and other inputs related to maize growing

Activity	Sub-activity	Work hours (h/ha) (wage: € 17.5/h)	Fix and variable machinery costs (€/ha)	Other inputs
Weed control-related activities:				
Chisel plough/Cultivator (4.5m)		0.44	24.17	
Mouldboard plough and packer (1.4m)		1.73	66.97	
Pesticide sprayer (24m)		0.17	6.90	
Harrow (9m)		0.17	11.09	
Hoe (6m)		0.72	30.03	
Other activities:				
Rating (share, every 5th year)		0.04	0.26	-
Manure application (25 m³/ha)		0.74	50.23	-
	Manure cost	-	-	€ 0.00/ha
Precision drill (6m-width)		0.53	41.72	-
Direct precision drill (59% increase with 20% discount for light soils)		0.53	66.31	
	Seed			€ 233.20/ha
Mounted fertiliser spreader (amount depends on $E(y)$)		0.00–0.29	0.00–6.14	
Liming (share, every 3rd year)		0.19	12.47	
	N			€ 1.10/kg
	P_2O_5			€ 0.87/kg
	K			€ 0.77/kg
	Ca			€ 0.05/kg
No harvest cost, sell ex field		-	-	-

Diesel use for mouldboard ploughing is assumed to be 30% higher/lower on heavy/light soils (for chisel ploughing 20%).

References: Achilles *et al.* (2016), fertiliser prices from LfL (2016), weight-shares from LWK NRW (2015b).

4 Results

Figure 2 presents for two price levels the chosen pre-sowing strategies as a share of municipalities where they are applied, on average of the two years *t*. Applying glyphosate in a strategy is on average optimal in about 5% to 22% of the municipalities. In the other municipalities, conservation tillage with mechanical strategies consisting mostly of one or two chisel ploughings is the most profitable. Glyphosate containing strategies are more profitable when applied closer to maize emergence, i.e. close before sowing or even close after sowing. The later maize emergences compared to weeds, the less glyphosate is applied. In case of a ban, the above mentioned mechanical strategies are used throughout, but mouldboard ploughing is not used in any year. As mechanical control suppresses weeds not as efficiently as herbicides, glyphosate use is higher in t_2 since the attainable yield is assumed higher in this year. As no alternative herbicides are licensed for pre-sowing, only mechanic control is observed under a ban.

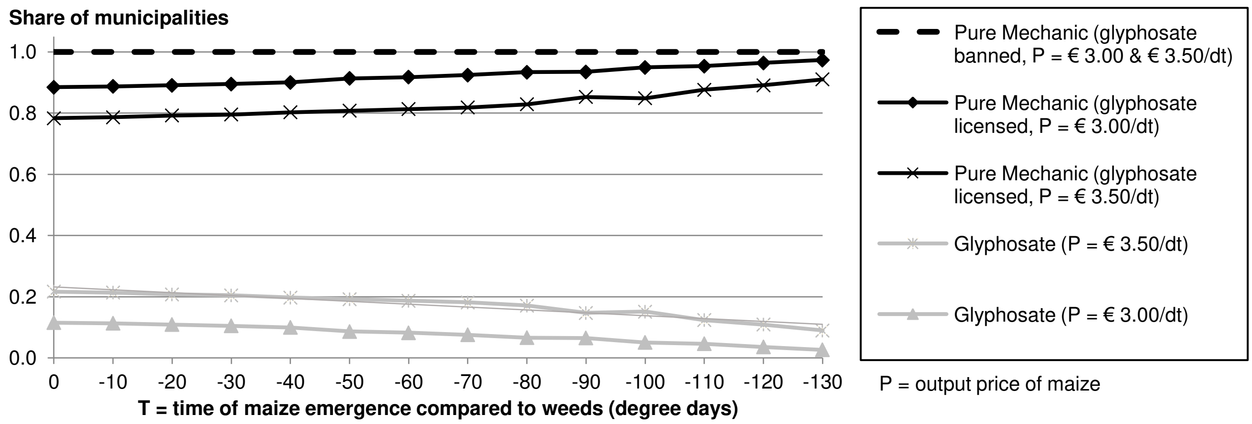

Fig. 2. Shares of used pre-sowing strategies (average of t_1 and t_2 of each municipality).

Regarding selective herbicide use after sowing, we observe that with a later emergence of silage maize compared to weeds, i.e. a higher weed pressure reflected by a more negative *T*, more expensive herbicide strategies get more profitable, i.e. the share of mechanical strategies decreases quickly (Figure 3). Higher silage maize prices reinforce this. Comparing the change from *T* from zero to -130, for example, implies an increase in weed control costs from € 86/ha up to € 113/ha at P=€ 3.50/dt, compared to an increase from € 76/ha to € 102/ha at P=€ 3.00/dt (not shown). The composition of the chosen strategies as a function of maize relative to weed emergence is summarised in Figure 4 for the glyphosate licensed-scenario and an output price of € 3.50/dt. In both scenarios, i.e. for glyphosate being licensed and banned, the most profitable AS shift from nicosulfuron, prosulfuron and S-metolachlor to terbuthylazine, mesotrione, pethoxamid, flufenacet, foramsulfuron, iodosulfuron and thiencarbazone.

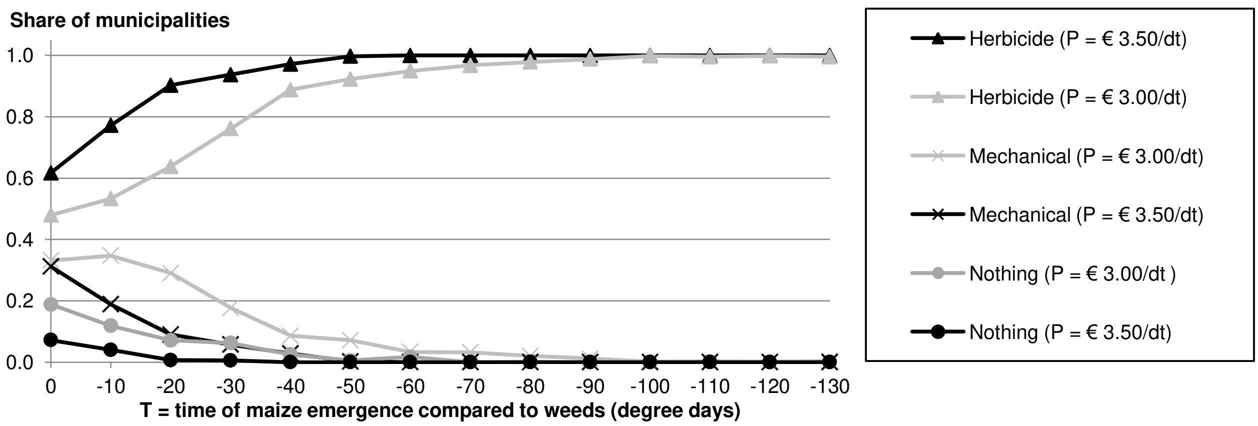

Fig. 3. Shares of post-sowing strategies as average of t_1 and t_2 (scenario with glyphosate licensed).

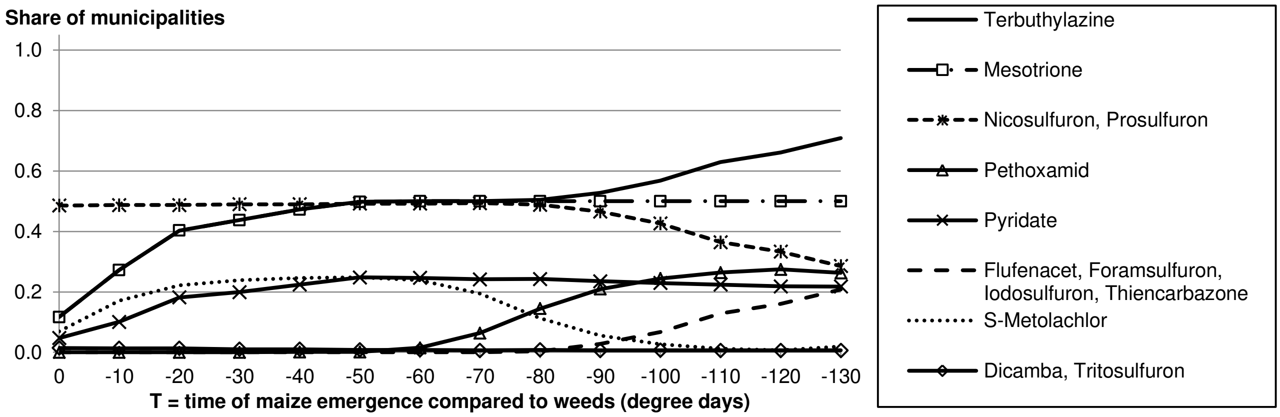

Fig. 4. Shares of post-sowing strategies (glyphosate licensed, P = € 3.50/dt, average of t_1 and t_2).

Table 3 shows the results of the hypothesis testing. Differences of mean values of the glyphosate using municipalities are given for different levels of *T* and for prices of € 3.00/dt and € 3.50/dt. H1 stated changes in post-sowing AS use after a ban. Indeed, the composition of the different AS changes in some municipalities, but those changes are overall not significant.

Table 3. Differences between glyphosate-ban-scenario and glyphosate-licensed-scenario (mean across glyphosate using municipalities) and results of hypothesis testing

	Maize emergence	**T=0**		**T=-20**		**T=-40**		**T=-60**		**T=-80**		**T=-100**		**T=-120**	
	Price	**3.00**	**3.50**	**3.00**	**3.50**	**3.00**	**3.50**	**3.00**	**3.50**	**3.00**	**3.50**	**3.00**	**3.50**	**3.00**	**3.50**
H1: share of municipalities (%)	No Herbicide	4.59	3.06	8.52	-	5.33	-	1.61	-	2.01	-	-	-	-	-
	Mechanic	-	2.45	2.43	-	5.33	-	1.61	-	2.01	-	-	-	-	-
	Nothing	4.59	0.61	6.08	-	-	-	.	-	-	-	-	-	-	-
	Herbicide	-4.59	-3.06	-8.52	-	-5.33	-	-1.61	-	-2.01	-	-	-	-	-
	Dicamba	-	-	-3.65	-	-	0.67	-	-	-2.01	-2.33	-5.25	1.75	-	-1.22
	Flufenacet	-	-	-	-	-	-	-	-	-	-	-	-0.88	-	-3.65
	Foramsulfuron	-	-	-	-	-	-	-	-	-	-	-	-0.88	-	-3.65
	Iodosulfuron	-	-	-	-	-	-	-	-	-	-	-	-0.88	-	-3.65
	Mesotrione	-	-	-	-5.10	-	-0.67	-	3.55	6.03	10.86	2.63	-1.75	7.37	7.30
	Nicosulfuron	-4.59	-3.06	-4.87	5.10	-5.33	-	-1.61	-3.55	-6.03	-8.53	2.63	0.88	-7.37	-2.43
	Pethoxamid	-	-	-	-	-	-	-	0.71	-	-6.20	-	-0.88	-	3.65
	Prosulfuron	-4.59	-3.06	-4.87	5.10	-5.33	-	-1.61	-3.55	-6.03	-8.53	2.63	0.88	-7.37	-2.43
	Pyridate	-	-	-	-1.91	-	-0.67	-	1.42	6.03	9.31	5.25	-2.63	3.68	3.65
	S-Metolachlor	-	-	-	-3.19	-	-	-	1.42	-	7.76	-2.63	1.75	3.68	-
	Terbuthylazin	-	-	-	-5.10	-	-0.67	-	3.55	6.03	10.86	2.63	-2.63	7.37	3.65
	Thiencarbazone	-	-	-	-	-	-	-	-	-	-	-	-0.88	-	-3.65
	Tritosulfuron	-	-	-3.65	-	-	0.67	-	-	-2.01	-2.33	-5.25	1.75	-	-1.22
H2: €/ha	Weed management costs	4.92 ***	4.64 ***	5.13 ***	4.46 ***	4.58 **	4.02 ***	5.49 **	3.95 **	6.20 **	2.80 *	2.94	2.66 *	0.56	3.26 *
H3: h/ha	Weed management labour demand	0.33 ***	0.32 ***	0.33 ***	0.34 ***	0.33 ***	0.33 ***	0.33 ***	0.31 ***	0.34 ***	0.31 ***	0.29 ***	0.32 ***	0.24 ***	0.32 ***
H4: €/ha	Gross margin per ha	-1.29	-1.71	-1.23	-1.56	-1.22	-1.58	-1.16	-1.46	-1.06	-1.25	-0.89	-1.12	-0.72	-1.11
H5: (%)	Yield difference (model yield minus real yield)	-0.7 **	-0.5 *	-0.6 *	-0.5	-0.7	-0.5	-0.7	-0.5	-0.6	-0.6	-0.8	-0.5	-0.8	-0.5

*, ** and *** represent 5%, 1% and 0.1% significance levels. No mark means that no significant difference occurred. Note that for tests on hypothesis H1, a Bonferroni correction was used.

Hypotheses: H1: average post-sowing strategies change in case of a glyphosate ban (average of t_1 and t_2),
H2: costs for weed management increase in case of a glyphosate ban (average of t_1 and t_2),
H3: working force demand increases in case of a glyphosate ban (average of t_1 and t_2),
H4: the gross margin decreases in case of a glyphosate ban (average of t_1 and t_2),
H5: yields decrease in case of a glyphosate ban (average of t_1 and t_2)

We cannot reject H2 that weed control becomes more expensive under a ban. We find that in municipalities where glyphosate was used in the benchmark, significantly more is spent on weed management under a ban. The effect decreases with the higher price of € 3.50/dt. The cost reduction stems from substituting glyphosate mostly with two passes of chisel ploughing, because sowing is assumed to be cheaper compared to only one pass of chisel ploughing (and also cheaper compared to glyphosate application only). This leads to a significant increase in labour demand and related costs (H3). That effect, however, decreases if *T* is lower, i.e. the weed pressure after sowing is high. In the latter case, more expensive post-sowing strategies with selected herbicides are used instead.

Generally, expected gross margins vary highly across municipalities reflecting yield differences. Furthermore, the later maize emerges compared to weeds, the lower the gross margin will be. On average over all municipalities under a glyphosate ban, decreases of the gross margin (including higher costs for labour) are with around € 1–2/ha minimal and overall not significant (see Table 3, row H4), with maximal reductions in single years of € 10/ha (for *P=3*) and € 12/ha (for *P=3.50*) (not shown).

The reduced plant protection intensity under a ban is reflected in decreased yields by about 0.5–1%, which turns out as more profitable than maintaining the control effort with more expensive strategies (difference is significant at higher levels of *T*).

5 Discussion

Our results present potential short-term effects in herbicide demand for weed control in silage maize production and thus can be used to quantify intensive margin effects of agri-environmental policies targeting single herbicides. Our normative model simulates limited yield losses at no extra costs for farmers under a glyphosate ban, matching the relatively low yield increasing effect of glyphosate reported in literature (Gehring *et al.*, 2012). In our model, this leads to a relatively high efficiency and widespread use of alternative conservation tillage strategies already under the benchmark. Under a glyphosate ban and profit maximising behaviour, overall control intensity and thus the expected maize yield would be somewhat reduced as maintaining the same level of weed suppression and the expected yield is too costly given the available alternative control strategies. Especially due to the subsidy induced boom in biogas production from silage maize in Germany (Gömann *et al.*, 2011), silage maize is currently in shortage, being regionally traded at relatively high prices in years with moderate yields. Reducing yields under a glyphosate ban would most probably drive prices further up, such that more costly weed control strategies could become profitable. Farmers might anticipate these impacts and intensify weed control beyond the current profit optimal point to avoid acting as buyers in the short maize markets. If we restrict the model such that a certain yield has to be achieved (a safety threshold to avoid large maize purchases), also more intensive plant protection intensities are used (with costs > € 120/ha) (not shown).

Compared to other studies being based on expert interviews (Kehlenbeck *et al.*, 2015; Schulte *et al.*, 2016), our results suggest lower additional costs; however, at an overall lower intensity of herbicide use. Kehlenbeck *et al.* (2015) estimated that a 75% increase of the glyphosate price would be necessary in order to cause a reduction of glyphosate use (in the profit equilibrium of glyphosate and plough use). The results of our normative, profit-maximising model suggest that already lower price increases would lead to use reductions. Indeed, already a 10% price increase leads to some reductions in use and at a 30% increase glyphosate was substituted by mechanical strategies in every municipality (for *T=-20* and *P=€ 3.50/dt*). This matches estimates of more elastic demand for herbicides (Böcker and Finger, 2017).

The observed treatment frequency in German maize production which measures the number of herbicide applications in relation to the area varied between 1.31–1.47 in 2011–2015, including preemergence treatments with glyphosate (JKI, 2016). Our model simulated lower average treatment frequencies over the two periods, which are, for instance between 0.75–1.11 at a level of *T=-20* and between 1.05–1.15 at *T=-100*. Pesticide intensities beyond the profit maximising intensity were reported by other authors (Jacquet *et al.*, 2011, for France; Skevas *et al.*, 2014, for the Netherlands) which could be explained by the risk-reducing effect of herbicides (Skevas *et al.*, 2014), not reflected in our profit maximising approach, but which should be addressed in future research.

JKI also reports the average share of the surveyed German farms which use a specific AS in maize production (JKI, 2016). For example in 2015, 33% of all surveyed farms used an herbicide strategy containing glyphosate, 91% used a strategy containing terbuthylazine, 50% used a strategy containing bromoxynil, etc. Our simulated shares over different levels of *T* differ partly from those values. For example, bromoxynil was not selected at all, but these differences could also root in our regional focus. Still, for selected AS, and depending on *T*, quite similar shares were calculated, e.g. for nicosulfuron, mesotrione, pethoxamid and partly for glyphosate and terbuthylazine.

Herbicide strategies considered in our model were aggregated to some extent, for instance by defining a two-time post-sowing herbicide application-strategy as one. Future approaches could further refine the strategies such as depicting each single application according to its characteristics and time of application. That asks, however, for improved data availability such as research on weed specific impact on yields. Additional data could also allow including more generally the control impact depending on doses of specific pesticides in the model. So far, reduced doses are only considered in some strategies which use doses below the manufacturers' recommendation. Also, we decided to neglect potential dynamic control impacts, for instance that a conservation tillage strategy might lead to higher weed abundance in the long-term (Schwarz and Pallutt, 2014) or that efficient control might depress future weed infestation (Swinton and King, 1994), as it is hard to properly account for external weed seed import in a single plot. Here, Hanzlik and Gerowitt (2011) find that geographical position and soil conditions have a higher influence on weed species composition compared to previous weed management.

Future research could apply the presented approach to other field crops and implement it into a whole farm context. Other aspects to be covered in future extensions are effects of fertilisation, of preceding or catch crops and of weed control measures in autumn.

6 Conclusions

The raster data of NetPhyD and BfN (2013) on weed occurrence are a valuable source to analyse weed spread in Germany. Combing this data with expert information on actual weed control management allows us to develop an output damage control approach for herbicide use in silage maize production for almost 380 municipalities in NRW. Simulating profit maximal weed control strategies in two consecutive years of maize cultivation with and without a glyphosate ban, we find that i) economic losses of a ban are limited for farmers currently applying glyphosate, ii) costs somewhat increase under a glyphosate ban as mechanical strategies for conservation tillage are used pre-sowing, while switches to more expensive selective herbicides in post-sowing strategies are simulated only in few cases. iii) Rather, somewhat lower yields reflecting decreased weed control turn out as profitable, which, however, could lead to higher regional maize prices. Finally, iv) demand of labour increases due to higher shares of mechanical strategies. If farmers do not behave risk neutral and instead use weed damage control additionally to reduce production and market risk, results might change. That highlights the need of further in-depth research on the topic.

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