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# A Meta-Analysis on the Elasticity of Demand for Pesticides

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## Abstract

There is an increasing policy interest in pesticide taxation schemes as a measure to reduce harmful effects of pesticide use. The effectiveness of such tax depends, however, on the price elasticity of demand for pesticides. Moreover, information on these demand elasticities and their determinants is of crucial relevance for policymaking and normative modeling approaches. In this article, we present a meta-analysis based on studies that have estimated pesticide demand elasticities in Europe and North America. Our meta-analysis reveals that the own-price elasticities of demand for pesticides are, with a median of -0.28, significantly smaller than zero, but also significantly larger than -1, *i.e.* to be inelastic. We find that the demand for pesticides for special crops is less elastic than that for arable and grassland. In addition, the demand for herbicides is more elastic than for other pesticides. Studies that consider only short-term horizons and little flexibility for farmers to adjust to price changes generate significantly less elastic pesticide demands. The results also indicate that more recent studies identify lower pesticide price elasticities of demand. Furthermore, we find that peer-reviewed studies tend to find more inelastic results compared to grey literature.

**Keywords:** Agricultural policy; demand analysis; meta-analysis; own-price elasticity of demand; pesticide tax; pesticides; robust regression.

## 1. Introduction

Reductions of harmful effects of pesticide use are high on agricultural policy agendas. For instance, national action plans have been established in countries of the European Union and pesticide taxation schemes have been established in some European countries (*i.e.* France, Sweden, Norway, Denmark) (Böcker and Finger, 2016; Lefebvre *et al.*, 2015). There have also been recent discussions on an introduction of a taxation scheme in other European countries such as Belgium, the Netherlands and Germany (ARCADIS Belgium, 2014; Hof *et al.*, 2013; Möckel *et al.*, 2015a,b). The effectiveness of such taxes depends on the demand response of farmers to higher pesticide prices. More specifically, low own-price elasticities of demand have been claimed to be a major hurdle for effective regulation of pesticide use via taxes (*e.g.* Falconer and Hodge, 2000; Fernandez-Cornejo *et al.*, 1998). Overviews of estimates of pesticide demand elasticities in developed countries have been provided in studies by Capalbo and Vo (1988), Falconer and Hodge (2000), Fernandez-Cornejo *et al.* (1998) and Hoevenagel *et al.* (1999). These overviews are cited frequently and serve as important references for assumptions made in normative modeling approaches (*e.g.* Möckel *et al.*, 2015a) and for comparison with positive studies (*e.g.* Muñoz Piña and Avila Forcada, 2004; Skevas *et al.*, 2012).

Despite the importance of these overviews for policy analysis and policy recommendations, there are several shortcomings and unexplored potentials. Most obviously, the existing overviews on pesticide demand elasticities are now outdated – the most recent being 2000.<sup>1</sup> Further limitations result from the fact that no comprehensive statistical meta-analyses on pesticide demand elasticities have been conducted.<sup>2</sup> Specifically, no distinction between short- and long-term elasticities has been made that accounts for farmers' flexibility to adjust to price changes, especially over longer time horizons. However, this distinction reflects crucial information for normative policy analysis of the effects of pesticide taxation (*e.g.* Möckel *et al.*, 2015a). Moreover, there has been no systematic analysis of differences of pesticide demand elasticities across

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<sup>1</sup> More recently, Skevas *et al.* (2013) presented an overview based on Fernandez-Cornejo *et al.* (1998), Hoevenagel *et al.* (1999) and Falconer and Hodge (2000), without adding further studies beyond 1997.

<sup>2</sup> The study by Bergh *et al.* (1997) presents a structured meta-analysis of some studies on pesticide demand elasticities, not covering the addressed points here empirically.

different agricultural systems and types of pesticides. In addition, no distinction between methodological approaches underlying demand elasticity estimates has been considered, despite the fact that a large variety of methodological approaches has been used to derive elasticities (*e.g.* econometric vs. optimisation models). Finally, no distinction between peer-reviewed and grey literature has been made. In this note, we aim to fill these gaps and provide a meta-analysis on pesticide demand elasticities. We focus on results from developed countries of the northern hemisphere to include estimates from comparable agricultural systems.

## 2. Methodology and Data

To identify relevant studies, we used bibliographic databases such as Scopus and Google Scholar, and the key words ‘pesticide’, ‘pesticide tax/levy/charge’ together with ‘elasticity’ (singular and plural). In total, 31 studies were identified that report original pesticide demand elasticities. We provide detailed argumentation on the inclusion and exclusion of studies in Appendix A.

From the selected studies, we obtained the following information, as available: (i) the year of publication, (ii) the period of analysis/data collection period, (iii) the country/region that was the subject of the analysis, (iv) the cropping system investigated, with classification into arable and grassland farming, special crops (horticulture, fruit production, viticulture), and an aggregate bundle when no specific production type was analysed, (v) the type of pesticide investigated, *i.e.* herbicides, fungicides, insecticides and pesticides in general, (vi) the considered flexibility/time span, *i.e.* short-term/fix or long-term/variable,<sup>3</sup> (vii) the estimated demand elasticity for pesticides, (viii) min–max values of these demand elasticity estimates, (ix) the method used, with distinction between econometric and normative models,<sup>4</sup> and (x) information on whether the study was peer-reviewed. Note that publications can be listed multiple times if they present

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<sup>3</sup> If time span and flexibility are not explicitly defined (self-declared) in the studies, the flexibility of variable inputs serves as a measure for long-term and short-term production. Therefore, longer periods of analysis or data collection periods can cover a short-term horizon if the variables in the models are assumed to be fixed.

<sup>4</sup> Normative approaches comprise mainly optimisation models such as linear programming approaches (profit maximisation or cost minimisation).

demand elasticities, for example, for different regions, agricultural systems, types of pesticides and/or use different methodologies.

We use a non-parametric Wilcoxon–Mann–Whitney test to identify differences across categories, *i.e.* differences between the size of the price elasticities. More precisely, we test if pesticide demand elasticities (i) are different from zero, (ii) differ across regions (Europe and North America), (iii) differ between long- and short-term horizons considered, (iv) differ across agricultural systems (arable and grassland, special crops and an aggregated sector), (v) differ between peer-reviewed and grey publications, and (vi) differ across methodological approaches (comparing econometric and normative models).

We conduct a multiple linear regression analysis to assess the most important determinants of pesticide demand elasticity estimates ( $\eta$ ) and to estimate marginal effects:

$$\eta(y, L, S, H, E, P, M) = \beta_0 + \beta_1 y + \beta_2 L + \beta_3 S + \beta_4 H + \beta_5 E + \beta_6 P + \beta_7 M + \varepsilon \quad (1)$$

Specifically, we consider the following variables as potential determinants of the estimates: the middle year of the analysis or data collection period with the base year being defined as 1900 ( $y$ ).<sup>5</sup> We include dummy variables for long-term horizon considered ( $L$ ), special crops (as agricultural systems with particularly high pesticide use levels) ( $S$ ), focus on herbicides ( $H$ ), European study ( $E$ ), peer-reviewed publication ( $P$ ), and the type of methodology (using a dummy for econometric analysis) ( $M$ ).  $b_0, \dots, b_7$  are the regression parameters that need to be estimated and  $\varepsilon$  represents the error term. Due to the considerable number of outlying observations in our study (see Fig. 1), we use MM-regression, a robust regression technique.<sup>6</sup> To account for the fact that some studies report more than one observation for some variables, cluster-adjusted variance-covariance matrices are used to derive standard errors. If a study reported a range or an interval for the same measure, mean values are used in both the regression analysis and

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<sup>5</sup> In addition, we also employed the year of publication, which produced similar results.

<sup>6</sup> The MM-estimator combines a high breakdown point S-estimator and an efficient M-estimator to obtain a high robustness (avoiding biases in coefficient estimates) against outlying observations by maintaining a high level of efficiency (*i.e.* maintaining low standard errors) (see, for example, Finger, 2010). The interpretation of coefficient estimates remains similar to a standard OLS regression.

the Wilcoxon–Mann–Whitney test, to avoid double counting (Table 1). All statistical analyses are conducted with R (R Core Team, 2015).

**Table 1.** Studies with pesticide demand elasticities

Author (publication year)	Land/region	Pesticide type (general or: f/fungicide, h/herbicide, i/insecticide (if appl. min. to max.))	Flexibility (long-term/ variable, short-term/fix)	Period of analysis/ data collection
Brown and Christensen (1981)	USA	-0.19 (-0.20 to -0.19)	Long-term	1947-1974
Schulte (1983)	Germany/Rhineland	f: -0.32 (-0.45 to -0.19)	Short-term	1978-1980
Schulte (1983)	Germany/Rhineland	f: -0.32 (-0.45 to -0.19)	Long-term	1978-1980
Schulte (1983)	Germany/Bavaria	f: -0.17 (-0.33 to 0.00)	Short-term	1978-1980
Schulte (1983)	Germany/Bavaria	f: -0.50 (-0.67 to -0.33)	Long-term	1978-1980
Schulte (1983)	Germany/Schleswig-Holstein	f: -0.21 (-0.27 to -0.14)	Short-term	1978-1980
Schulte (1983)	Germany/Schleswig-Holstein	f: -0.53 (-0.80 to -0.25)	Long-term	1978-1980
Schulte (1983)	Germany/South Oldenburg	f: -0.32 (-0.44 to -0.20)	Short-term	1978-1980
Schulte (1983)	Germany/Hessen	f: -0.63 (-0.76 to -0.50)	Long-term	1978-1980
Antle (1984)	USA	-0.19	Long-term	1910-1946
Antle (1984)	USA	-0.25	Long-term	1947-1978
Dubgaard (1987)	Denmark	-0.30	Long-term	1971-1985
Dubgaard (1987, 1991)	Denmark	h: -0.69	Long-term	1971-1985
Capalbo (1988)	USA	-0.19	Long-term	1948-1983
Capalbo (1988)	USA	-0.88	Long-term	1948-1983
Capalbo (1988)	USA	-0.41	Long-term	1948-1983
Capalbo (1988)	USA	-0.47	Long-term	1948-1983
Capalbo (1988)	USA	-0.61	Long-term	1948-1983
Capalbo (1988)	USA	-0.70	Long-term	1948-1983
Elhorst (1990)	Netherlands	-0.29	Short-term	1980-1986
Aaltink (1992), Master's thesis, cit. from Oskam <i>et al.</i> (1992)	Netherlands	-0.13 (-0.23 to -0.03)	Short-term	unknown
Aaltink (1992), Master's thesis, cit. from Oskam <i>et al.</i> (1992)	Netherlands	-0.39 (-0.55 to -0.23)	Long-term	unknown
Aaltink (1992), Master's thesis, cit. from Oskam <i>et al.</i> (1992)	Netherlands	-0.39 (-0.55 to -0.23)	Long-term	unknown
McIntosh and Williams (1992)	USA/Georgia	-0.11	Long-term	1950-1986
Oskam <i>et al.</i> (1992)	Netherlands	-0.21	Short-term	1970-1988
Oskam <i>et al.</i> (1992)	Netherlands	-0.22	Medium-term	1970-1988



**Table 1.** (*continued*)

Author (publication year)	Land/region	Pesticide type (general or: f/fungicide, h/herbicide, i/insecticide (if appl. min. to max.))	Flexibility (long-term/ variable, short-term/fix)	Period of analysis/ data collection
Oskam <i>et al.</i> (1992)	Netherlands	-0.22	Long-term	1970-1988
Oskam <i>et al.</i> (1992)	Netherlands	-0.25	Short-term	1970-1988
Oskam <i>et al.</i> (1992)	Netherlands	-0.26	Medium-term	1970-1988
Oskam <i>et al.</i> (1992)	Netherlands	-0.29	Long-term	1970-1988
Rude (1992)	Denmark	-0.20 (-0.22 to -0.17)	Short-term	1987-2004
Rude (1992)	Denmark	-0.24 (-0.27 to -0.20)	Medium-term	1987-2004
Rude (1992)	Denmark	-0.28 (-0.32 to -0.23)	Long-term	1987-2004
Villezca-Becerra and Shumway (1992)	USA/California	-0.09	Long-term	1951-1982
Villezca-Becerra and Shumway (1992)	USA/Florida	-0.17	Long-term	1951-1982
Villezca-Becerra and Shumway (1992)	USA/Iowa	-0.04	Long-term	1951-1982
Villezca-Becerra and Shumway (1992)	USA/Texas	-0.21	Long-term	1951-1982
Fernandez-Comejo (1993)	USA/Illinois	-0.10	Short-term	1949-1982
Fernandez-Comejo (1993)	USA/Illinois	-0.10	Short-term	1949-1982
Fernandez-Comejo (1993)	USA/Illinois	-0.12	Long-term	1949-1982
Fernandez-Comejo (1993)	USA/Illinois	-0.38	Long-term	1949-1982
Fernandez-Comejo (1993)	USA/Indiana	-0.08	Short-term	1949-1982
Fernandez-Comejo (1993)	USA/Indiana	-0.08	Short-term	1949-1982
Fernandez-Comejo (1993)	USA/Indiana	-0.09	Long-term	1949-1982
Fernandez-Comejo (1993)	USA/Indiana	-0.60	Long-term	1949-1982
Chambers and Lichtenberg (1994)	USA	-1.53	Long-term	1949-1990
Chambers and Lichtenberg (1994)	USA	-1.50	Long-term	1949-1990
Chambers and Lichtenberg (1994)	USA	0.05	Long-term	1949-1990
Chen <i>et al.</i> (1994)	USA/Alabama	-2.42	Long-term	1949-1986
Gren (1994a)	Sweden	h: -0.97	Long-term	1950-1989
Gren (1994b)	Sweden	h: -0.93	Long-term	1948-1989
Oude Lansink (1994)	Netherlands	-0.12	Short-term	1970-1988

**Table 1.** (*continued*)

Author (publication year)	Land/region	Pesticide type (general or: f/fungicide, h/herbicide, i/insecticide (if appl. min. to max.))	Flexibility (long-term/ variable, short-term/fix)	Period of analysis/ data collection
Papanagiotou <i>et al.</i> (1994)	Greece	-0.28	Short-term	1961-1990
Papanagiotou <i>et al.</i> (1994)	Greece	-0.28	Short-term	1961-1990
Shumway and Chesser (1994)	USA/Texas	h: -0.70 (-2.00 to +0.60)	Long-term	1972-1986
Bauer <i>et al.</i> (1997)	Germany/Hessen	f: -0.02	Short-term	1991-1993
Carpentier and Weaver (1997)	France/Ile-de-France, Centre,	-1.55 (-1.97 to -1.13)	Long-term	1987-1990
Falconer (1997), Dissertation cit. from Falconer (1998)	UK/East Anglia	-0.20 (-0.30 to -0.10)	unknown	unknown
Komen <i>et al.</i> (1997)	Netherlands	-0.14	Short-term	1990
Komen <i>et al.</i> (1997)	Netherlands	-0.11	Short-term	1990
Komen <i>et al.</i> (1997)	Netherlands	-0.25	Long-term	1990
Oude Lansink and Peerlings (1997)	Netherlands	-0.48	Long-term	1970-1992
Russell <i>et al.</i> (1997)	UK/North West	-1.11 (-1.12 to -1.09)	Short-term	1989-1993
Jacquet <i>et al.</i> (2011)	France	-0.77 (-1.25 to -0.28)	Combined	2002-2007
Ivanova <i>et al.</i> (2012)	Bulgaria	-0.11 (-0.12 to -0.09)	Long-term	2002-2008
Ivanova <i>et al.</i> (2012)	Bulgaria	-0.16 (-0.19 to -0.12)	Long-term	2002-2008
Ivanova <i>et al.</i> (2012)	Portugal	-0.19 (-0.22 to -0.16)	Long-term	2002-2008
Ivanova <i>et al.</i> (2012)	Portugal	-0.20 (-0.23 to -0.16)	Long-term	2002-2008
Skevas <i>et al.</i> (2012)	Netherlands	-0.02 (-0.03 to -0.0003)	Short-term	2003-2004
Fadhuile <i>et al.</i> (2015)	France	h: -0.63	Long-term	2001
Fadhuile <i>et al.</i> (2015)	France	h: -0.68	Long-term	2006
Femenia and Letort (2016)	France/Meuse	-0.17 (-0.24 to -0.10)	Long-term	2007-2012

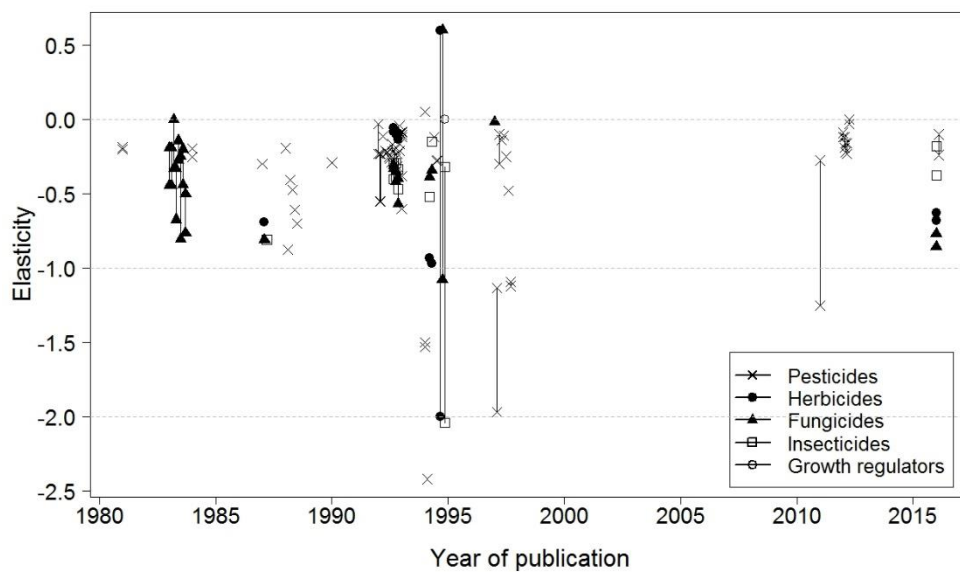
### 3. Results

Table 1 lists the studies that are included in the meta-analysis and some selected variables. Note that the tables with the complete information collected, as well as the codes for statistical analyses, are available in Appendices B to C. Fig. 1 presents the elasticities across all studies by the publication year of the studies and type of pesticides considered.

The median elasticity across all studies is -0.28. Using the Wilcoxon-Mann-Whitney test, we can reject the null-hypotheses that the elasticity is equal or  $>0$  at the 1% level. Fig. 1 shows that the vast majority of studies appeared in the 1990s, though more recent studies exist for Europe, which reflects the re-emerging policy relevance of the pesticide demand regulation. Despite the fact that some studies report on particular types of pesticides or even on individual products (*e.g.* Shumway and Chesser, 1994), the majority of studies present elasticities for pesticides in general so that no patterns can be observed.

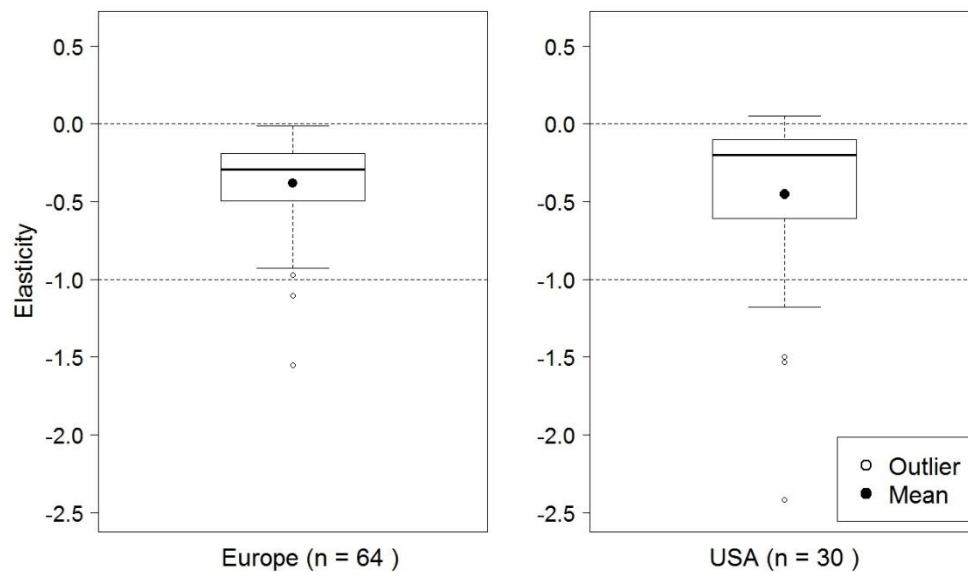
Fig. 2 presents the distribution of demand elasticities by continent. European studies (22 studies, 64 observations) dominate over North American studies (nine studies, 30 observations, only USA) in quantity. The median of demand elasticities is lower in the US (-0.20) than in Europe (-0.30). However, the variability within the US studies is larger, with an interquartile range of 0.51 compared to 0.30 for Europe. The null-hypothesis of no differences across continents cannot be rejected.

Fig. 3 presents the distribution of demand elasticities with respect to input flexibility and time horizon assumed in the studies. We find that the majority of studies analyse long-term effects, accounting for various possibilities to adjust the production system and techniques. As expected, the longer-term perspectives result in more elastic pesticide demand estimates (median = -0.39) compared to short-term perspectives (median = -0.18). The null-hypothesis of no differences across time horizons is rejected at the 1% level of significance.

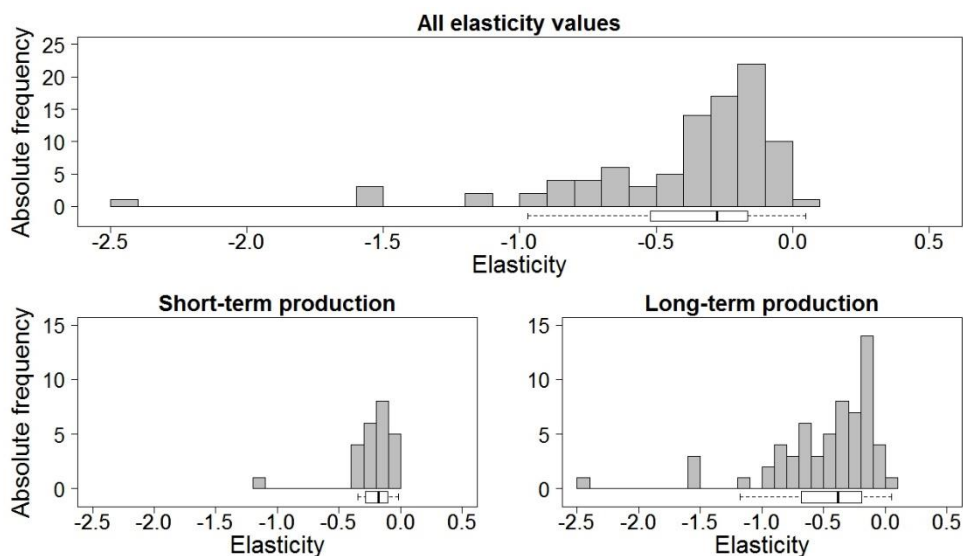


**Fig. 1.** Pesticide's own-price elasticities of demand following the year of publication.

*Note:* The lines between two observations refer to an interval because of different elasticity values for different levels of price changes.



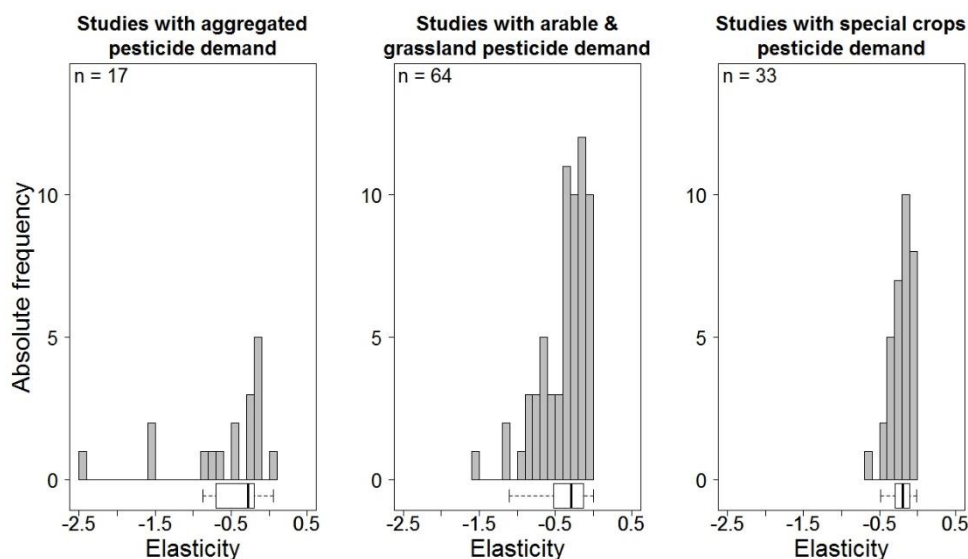
**Fig. 2.** Pesticide's own-price elasticities of demand for Europe and the USA.



**Fig. 3.** Pesticide's own-price elasticities of demand arranged by flexibility of production.

Fig. 4 shows demand elasticity estimates by agricultural system investigated. We find that the demand for pesticides in special crops is less elastic (median = -0.19) than for arable and grassland production (median = -0.30) and pesticide use in aggregate (*e.g.* across the entire farm, median = -0.28). Comparing the demand elasticities in special crops with arable and grassland production, we reject the null-hypothesis of equal demand elasticities at the 5% level of significance. Moreover, a significant difference can also be found between the aggregate use and special crops (5% level), but not between aggregate use and arable production.

Concerning the analysis of the methodologies underlying pesticide demand elasticity estimation, we find 38 observations for econometric approaches (median = -0.30) and 39 observations for normative approaches (median = -0.21). There is a tendency towards lower elasticities in normative approaches with a significance level of 5%. Regarding the publication channel, we find that demand elasticities reported in peer-reviewed studies indicate on average a less elastic pesticide demand (33 observations, median = -0.21) compared to non-peer-reviewed publications (61 observations, median = -0.29). However, this difference is not significant using a Wilcoxon–Mann–Whitney test.



**Fig. 4.** Subject of analysis in studies estimating pesticide's own-price elasticities of demand.

Finally, we conducted the regression analysis including all of these factors. We find that the explanatory variables 'middle year of the analysis period' and 'peer-review' are not independent of each other. More specifically, peer-reviewed studies are more often observed to be more recent studies with more recent middle years of the analysis. Thus, we present both models with either the middle year of analysis or a dummy for peer-review being included. In addition, the consideration of the methodology used (dummy Econometric analysis) results in several missing observations. As sensitivity analysis, we therefore estimate our models with and without the consideration of this variable. Coefficient estimates of the four models are presented in Table 2. We find pesticide demand to be less elastic when published in peer-reviewed journals. Along these lines, we also find evidence that studies analysing more recent data obtain significantly inelastic demand. Note that the intercepts in Model 1 and 3 refer to the year 1900. Moreover, studies considering a long-term horizon result in more elastic demand elasticity estimates. We find the demand for pesticides in special crops to be less elastic compared to other agricultural sectors, and demand for herbicides is more elastic than for other pesticides. European studies tend to result in more elastic demand estimates, though significance

tests are ambiguous. Even though econometric studies tend to result in less elastic demand elasticity estimates, we do not find a significant effect of the methodology used.<sup>7</sup>

**Table 2.** Parameter estimates of the regression models (marginal values)

Parameter	Model 1	Model 2	Model 3	Model 4
$\beta_0$ (intercept)	-0.627 (-11.016)***	-0.216 (-5.068)***	-0.420 (-2.381)**	-0.201 (-4.819)***
$\beta_1$ (middle year of analysis)	0.007 (12.241)***	–	0.004 (1.738)*	–
$\beta_2$ (long-term)	-0.173 (-5.610)***	0.212 (-7.232)***	-0.177 (-5.198)***	-0.215 (-7.743)***
$\beta_3$ (special crops)	0.106 (2.279)**	0.119 (3.316)***	0.086 (1.789)*	0.108 (4.022)***
$\beta_4$ (herbicides)	-0.416 (-7.555)***	-0.406 (-5.906)***	-0.262 (-1.955)*	-0.308 (-3.179)***
$\beta_5$ (Europe)	-0.207 (-4.854)***	-0.044 (-1.146) (n.s.)	-0.200 (-2.693)***	-0.058 (-1.495) (n.s.)
$\beta_6$ (peer-review)	–	0.184 (6.908)***	–	0.194 (5.029)***
$\beta_7$ (econometric method)	0.042 (1.587) (n.s.)	0.030 (0.979) (n.s.)	–	–
Degrees of freedom	60	60	74	74

Notes: Values in parentheses are z-values. n.s. denotes not significant. \*, \*\* and \*\*\* denote significance at the 10%, 5% and 1%, level, respectively. The package ‘MASS’ was used for MM-estimation. The package ‘multiwayvcov’ was used for the derivation of the cluster-adjusted standard errors. The R-code for the regressions can be found in Appendix D.

Note that the few studies that report the uncertainty attached to pesticide demand elasticity estimates (*e.g.* as standard deviation) often report large levels of variability of these estimates (see Appendix C). Besides the considerable degree of across study-heterogeneity, there is also large within-study heterogeneity. Thus, generalising from point estimates needs careful reflection and highlights the importance of analysing different pesticide types and products or different areas of application.

<sup>7</sup> As there might be a bias towards econometric analyses among peer-reviewed studies, we estimated the model without the dummy for either peer-review or econometric studies, but find no change in coefficient estimates or levels of significance.

## 4. Discussion and Conclusions

Our meta-analysis reveals that own-price elasticities of demand for pesticides are, with a median of -0.28, significantly smaller than zero, but also to be significantly larger than -1, *i.e.* are inelastic. Moreover, demand elasticity estimates are found to be highly heterogeneous across different studies, ranging from complete inelasticity to relatively high elasticity, reflecting the fact that various parameters affect pesticide application. Other developments, such as the development of new pesticides or the occurrence of new pests might even be more important than price developments. For example, Vijftigschild and Oskam (1994) show for the Netherlands that between 1980/81 and 1991/92, despite pesticide prices increased up to 32.5%, the pesticide demand increased by 20%, which would indicate a simple and crude elasticity of +0.63. In a similar vein, pesticides taxes have not necessarily led to sharp decreases in pesticide use, as observed in Sweden and Denmark under the former tax scheme, but, rather, to a substitution of products, as observed in Norway (Böcker and Finger, 2016).

Nevertheless, our results show that demand elasticities are significantly smaller than zero so that, *ceteris paribus*, there will be a quantity reduction if pesticide prices are increased. This indicates that taxation of pesticides will have an effect of reducing pesticide use. However, the finding of inelastic demand for pesticides also indicates that large levels of taxation are required to realise substantial quantity reductions. The meta-analysis also identifies specific agricultural production environments, where the elasticity of the demand for pesticides is almost zero (*e.g.* Skevas *et al.*, 2012), and where the effectiveness of taxation will be limited. This finding highlights the importance of country-specific ex-ante analyses of policy measures. Our meta-analysis reveals a large heterogeneity of the magnitude of these effects. More specifically, we find that price elasticities of demand are more inelastic in special crops (horticulture, fruit production and viticulture) compared to arable and grassland farming. This is especially relevant since special crops usually need the largest amount of pesticides per hectare – particularly more fungicide and insecticide but less herbicide. The lower elasticity can be explained due to the fact that (i) fruit production and viticulture are spatially less flexible in production than other crops, (ii) the harvest is more valuable and quality aspects are more



important (*e.g.* Weston and Barth, 1997), (iii) pesticides are applied more often preventively, and (iv) fewer substitutes exist for those sectors. This finding also highlights that a pesticide tax could imply non-uniform income effects on farms, *e.g.* comparing farmers growing special crops and arable farmers. Our results show that herbicide demand is more elastic than fungicides and insecticides. Thus, taxation might be particularly suited to reducing herbicide use. Next to the heterogeneity across crops and pesticide type, also a considerable heterogeneity of demand elasticities across time was revealed in our analysis. In the short-run, the median demand elasticities are significantly less elastic than in the long-run, which is in line with Le Chatelier's principle generalised by Samuelson (1983). We find that estimated demand elasticities significantly decreased over time (middle year of the analysis period) and with peer-review. Even though it is not possible in our analysis to identify causalities and determinants for this development, the finding is in line with qualitative observations made in Skevas *et al.* (2012) and Fadhuile *et al.* (2016). Skevas *et al.* (2012) argue that demand elasticities are lower due to increasing importance of pesticides in current agricultural production practices in comparison to earlier decades. Fadhuile *et al.* (2016) argue that stricter policies result in smaller numbers of available pesticides, *i.e.* a decreasing number of substitutes, which leads to more inelastic demand. Thus, in these situations, pesticide taxes may have a limited effectiveness. However, pesticide taxes may also promote changed behaviour towards more agronomical, biological or mechanical plant protection measures.

Despite the fact that policy-makers often aim to reduce the use of toxic pesticides and not necessarily the quantity of all aggregated pesticides, little information about demand differences with respect to the toxicity of the pesticides was found in our research: only Skevas *et al.* (2012) show that the demand elasticity is smaller for more toxic pesticides (-0.0003 vs. -0.03 for less toxic ones). Future research should focus on this aspect, because for policy implications, it motivates a taxation approach that accounts for the toxicity of different pesticide products, as implemented in Norway, Denmark and France.

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## Appendix

Additional Supporting Information may be found in the online version of this article: <https://doi.org/10.1111/1477-9552.12198>.

### *Appendix A:*

#### **Additional notes to the selection of studies**

More studies were found which simulate price increases on pesticides, but elasticities could not be derived, because the pre-tax costs are unknown (*e.g.* by a tax: Archer and Shogren (2001) simulate different tax systems). Dubberke and Schmitz (1993) report a price elasticity of -0.777, which however is not significant at the 10% level. Moreover, Zeddies *et al.* (1992) simulate for winter wheat in Germany that a relative price increase of 1.5 would lead to zero pesticide use. However, the results are criticised by themselves as not realistic in practice. During the literature analysis, also some studies outside the North America and Europe were found giving examples for pesticide elasticities (*e.g.* the analyses of Antle and Pingali (1994) and of Tjornhom *et al.*, 1998 for the Philippines). Those studies are not included.

In comparison to other studies, we have not included the following publications: We were not able to find any (original) information about price elasticities of demand in Lichtenberg *et al.* (1988), Pettersson *et al.* (1989) and Carpentier (1994) and thus excluded them from the analysis. The studies of Hazilla and Kopp from 1986, Johnsson from 1991, and ECOTEC from 1997 were not found in the literature search. The preliminary study of the Dutch DHV and LUW from 1991 was replaced by Oskam *et al.* (1992). The latter is included in the analysis.

**Appendix B:****Data collected from studies as CSV-file (Online)****Appendix C:****Table with studies reporting a standard deviation of elasticity results****Table A1.** Studies reporting a standard deviation of elasticity results

Author	Elasticity	SD	SD/Elasticity
Antle (1984)	-0.194	0.354	-1.82
Antle (1984)	-0.254	0.204	-0.80
McIntosh and Williams (1992)	-0.112	0.034	-0.30
Oskam <i>et al.</i> (1992)	-0.210	0.150	-0.71
Oskam <i>et al.</i> (1992)	-0.220	0.150	-0.68
Oskam <i>et al.</i> (1992)	-0.220	0.150	-0.68
Oskam <i>et al.</i> (1992)	-0.250	0.190	-0.76
Oskam <i>et al.</i> (1992)	-0.260	0.190	-0.73
Oskam <i>et al.</i> (1992)	-0.290	0.190	-0.66
Oude Lansink (1994)	-0.120	0.080	-0.67
Papanagiotou <i>et al.</i> (1994)	-0.279	0.163	-0.58
Papanagiotou <i>et al.</i> (1994)	-0.276	0.157	-0.57
Fadhuile <i>et al.</i> (2016)	-0.629	0.027	-0.04
Fadhuile <i>et al.</i> (2016)	-0.856	0.009	-0.01
Fadhuile <i>et al.</i> (2016)	-0.374	0.025	-0.07
Fadhuile <i>et al.</i> (2016)	-0.681	0.029	-0.04
Fadhuile <i>et al.</i> (2016)	-0.769	0.009	-0.01
Fadhuile <i>et al.</i> (2016)	-0.182	0.033	-0.18

## *Appendix D:*

### **R code for the regression analysis**

```

# Load file, but adjust filename and header names before
elasticity <- read.csv("C:/filename.csv", header=T)

#-----
# REGRESSION ANALYSIS
#-----

attach(elasticity)

### Performing robust MM-regression:

# load package 'MASS'
library(MASS)
elasticity$ESY <- (elasticity$EndY + elasticity$StartY)/2
rfit <- rlm(Elas ~ ESY + Longterm + Special + Herbicides + EU + Journal + Econometric,
data=elasticity, method="MM")
summary(rfit)

### Estimate cluster-adjusted variance-covariance matrices to derive:

standard errors
# Load packages 'multiwayvcov' and 'lmtest'
library(multiwayvcov)
library(lmtest)
# rfit is the rlm element
# Author is the ID, which is used for clustering
ml.vcovCL<-cluster.vcov(rfit,Author)
# Apply new z tests
coeftest(rfit, ml.vcovCL)

```

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