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Extreme heat reduces insecticide use under real field conditions

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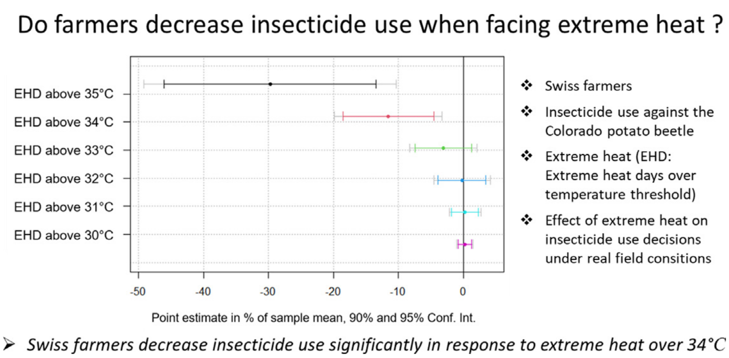
HIGHLIGHTS

- Insecticide use is expected to increase in a warming climate.
- We show that it declines substantially under extreme heat: 11.5% for each EHD > 34 °C.
- Example of insecticide use against the Colorado potato beetle in Swiss potatoes.
- Results account for adaption decisions of farmers under real field conditions.
- Importance of increasing weather extremes for pesticide use under climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Insecticide use and its adverse environmental and health effects are expected to further increase in a warming climate. We here show that farmers' insecticide use, however, declines substantially when facing extreme heat. Using the example of Colorado potato beetles (*Leptinotarsa decemlineata*) in Switzerland, we find an 11.5% reduction of insecticide use for each day and degree that maximum temperatures exceed 34 °C in the potato growing season. Importantly, our analysis accounts for farmers' behavior under real field conditions, considering the potential adaption of farming practices to extreme heat. It, therefore, highlights how to combine methods to assess and improve our knowledge on the combined major challenges of reducing pesticide risks and coping with the effects of climate change on agriculture while accounting for human behavior. In the analysis, we provide various robustness checks with regard to the definition of temperature extremes, pesticide use indicators, and the chosen statistical model. We further distinguish the principal drivers of the identified effect and find strong evidence that insecticide use reductions are mainly driven by heat-induced decreases in pest pressure rather than heat-induced yield losses that render insecticide applications too expensive. We conclude that similar investigations for other crops and countries are required to assess and understand farmers changing pesticide use decisions under climate change.

1. Introduction

Agricultural insecticide use is threatening the environment and human health on a global scale (e.g. Larsen et al., 2017; Tang et al., 2021), and several countries have implemented reduction targets in response (Möhring et al., 2020). Pest pressure from insects on major crops is projected to further increase under climate change, especially in regions with a relatively cool climate (e.g. Deutsch et al., 2018; Pulatov et al., 2016; Wang et al., 2017). Increases in pest pressure may lead to increased insecticide use and thus higher risks for human health and the environment. It is,

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therefore, key for the design of effective and efficient tools and policies for pesticide risk reduction to understand farmers changing pesticide use decisions under climate change.

Previous studies have mainly focused on the relationship between increasing average surface temperatures, pest pressure, and insecticide use under climate change (Deutsch et al., 2018). However, climate change not only increases average temperatures but also exacerbates risks of extreme temperature events (e.g. Fischer et al., 2013; Ma et al., 2021; IPCC, 2021). Extreme heat may, for example, reduce pest pressure on crops (Parratt et al., 2021; Zhang et al., 2015). Furthermore, extreme heat can not only affect pest pressure but also have severe effects on crop yields and, therefore, more generally, farmers' crop management decisions (Schlenker and Roberts, 2009). To assess the impact of extreme heat on insecticide use, it is therefore essential to consider farmer behavior, i.e. their adaption decisions of farmers under real field conditions.

We here provide the first empirical quantification of the effect of extreme heat events on insecticide use under real field conditions. Our analysis accounts for key adaptation responses of the ecosystem and the farmers' pest management behavior, using field-level records of insecticide use. To assess the impact of extreme heat on insecticide use, we use ten years of plot-level panel data (886 field and 276 farm-year observations) on weather and insecticide use decisions of Swiss non-organic farmers against the Colorado Potato Beetle (*Leptinotarsa decemlineata)* in potato production (*Solanum tuberosum*). To identify causal effects, we estimate a panel model with year and farm fixed effects (Schlenker and Roberts, 2009), thus controlling e.g. for farm size, input use intensity, variety choice, management measures, soil type, farmer behavior, and policy and price changes.

The Colorado potato beetle is one of the major insect pests in agriculture, responsible for substantial economic damages and a high share of global insecticide use. Only control costs can, for example, be up to around 200 CHF per year and hectare in Switzerland (Mouron et al., 2013). Its importance is expected to grow due to its rapid expansion and growing resistance to insecticides (Cong et al., 2020) further – and it has therefore previously been chosen to illustrate the effects of climate on pest pressure (Wang et al., 2017).

Our main finding is that Swiss farmers reduce their insecticide use against the Colorado potato beetle substantially when facing extreme heat (11.5% for each degree and day above 34 °C in the potato growing season). Our study thus highlights the importance of increasing extreme weather events for pesticide use under climate change and provides an approach how to quantify its impacts under real field conditions.

Following, we present methods and data used. We then present and discuss our results and finally conclude on the implications of our findings.

2. Methods & data

To identify the causal effect of temperature exposure on insecticide use, we follow Schlenker and Roberts (2009) and use a fixed-effects regression model.

To model nonlinear temperature effects (heat exposure), we use the concept of “extreme heat degree days.” This indicator has been broadly used to identify the potentially nonlinear effect of extreme heat on agriculture[1] (see e.g. Lobell et al., 2013; Roberts et al., 2013; Roberts et al., 2017) and has been proven to capture heat stress in various crop production systems. It is computed as the daily maximum temperature exceeding a given temperature threshold, summed up for each day of the whole potato growing season (April–August for Swiss potatoes). This indicator thus gives a proxy for spatially explicit extreme heat exposure of farms. Further, we measure insecticide use (against potato beetles) in terms of quantities of active ingredients in our main model (and use other pesticide use indicators as robustness checks).

In the analysis, we control for potential nonlinear effects of precipitation, as well as all variables that change over farms, farmers, and years with fixed effects. The latter may, for example, include farm size, input use intensity, variety choice, management measures, soil type, farmer behavior, and policy and price changes. To identify the effect of extreme heat on insecticide use, we then estimate the following model:

$$y_{itk} = \alpha_{ik} + \beta_k EHD_{itj} + \gamma_{1k} PREC_{it} + \gamma_{2k} PREC_{it}^2 + \varphi_{tk} + \varepsilon_{it} \quad (1)$$

where *y_itk* is insecticide use against potato beetles on farm *i* in year *t* measured with pesticide indicator k, α_ is the farm-fixed effect, EHD_{itj} are extreme heat days above temperature threshold *j* for farmer *i* in year *t*, $PREC_{it}$ is the precipitation sum over the growing season for farmer *i* in year *t*, *φ_tk* is the year-fixed effect, ε_it is the residual error term and β_k, γ_{1k} and γ_{2k} are the respective regression coefficients.

To estimate the model, we use a panel fixed-effects estimator and cluster standard errors by year to allow for potential correlation in space. β_k is the coefficient of interest, which indicates the effect of an additional extreme heat day (maximum temperature exceeding the temperature threshold by an additional degree and day in the growing season) on insecticide use. We expect significant negative effects of insecticide use above 34 °C in line with experimental results for heat effects on potato beetle populations (Logan et al., 1985).

As a robustness check for nonlinear temperature effects, we separately estimate the same models multiple times, only adjusting the temperature threshold for the computation of extreme heat-days (Blanc and Schlenker, 2017). We choose $j \in [30;35]$ as a reasonable bandwidth around 34 °C.[2] Additionally, we not only account for quantities of insecticides used but also for their potential environmental and health risks. For the latter, we use the Load indicator, which has been established in Denmark for years as an official indicator to measure risk reduction targets and to set pesticide tax levels (Kudsk et al., 2018). More specifically, we compute the Human Health Load, the Ecotoxicity Load, the Fate Load, and the Pesticide Load Index, i.e. the sum of the three sub-indicators using the R-Package PesticideLoadIndicator (Möhring et al., 2021). Further, we check the robustness of our estimates with regard to potential omitted variable bias using Oster bounds (Oster, 2019).

Although we control for potential effects of precipitation, farm-, farmer- and year-specific effects, such as farm size, input use, varieties, management, soil type, farmer behavior, and changes in prices in our analysis, estimation results may potentially suffer from omitted variable bias. To assess the robustness of our analysis to omitted variable bias, we, therefore, calculate Oster bounds for all of our main regression results (Oster, 2019). More specifically, we use the “robomit” package in R (Schaub, 2020) to calculate the delta indicator. The indicator is described in Oster (2019) as the degree to which unobserved variables would have to exceed the explanatory power of all variables in the regression, including control variables, to render the effect of heat stress exposure zero.

Finally, we investigate the underlying mechanism in insecticide use reductions more closely. Insecticide use reductions might not be due to heat-induced reductions in insect populations but economic considerations, i.e., heat-induced yield losses that render insecticide applications too expensive. We calculate minimum infestation levels necessary to reach economic application thresholds based on observed plot-level potato yields (i.e., realized end-of-season yields, accounting for potential heat-induced crop losses), average potato and insecticide application prices, as well as average insecticide efficacy and minimum damages of L. *decemlineata* found in field trials for Swiss potatoes (Mouron et al., 2013). Control costs against the Colorado potato beetle can amount up to 200 CHF per hectare in Switzerland (Mouron et al., 2013).

For or analysis, we use a rich panel data set on plot-level crop-management decisions of Swiss potato producers from the Swiss Central Evaluation of Agricultural Indicators (de Baan et al., 2015). The data includes observations on 886 potato plots (53 farmers, 276 farm-year observations) from 2009 to 2018 (e.g. Möhring et al., 2019). We focus on

[1] Note that the indicator is sometimes also called “extreme degree days”, “high heat degree days” or “cooling degree days” indicator (e.g. Lobell et al., 2013; Roberts et al., 2017).

[2] Note that higher thresholds above 35°Celsius cannot be used due to the lack of occurrences in the Swiss regions sampled.

potato beetles as a major insect pest, which is responsible for severe economic damages and a large share of insecticide use globally. In computing insecticide use against the Colorado potato beetle, we take a conservative approach and exclude products, which are also registered for use against other pests (also considering these products does not affect estimates – results available upon request). We further use high-resolution daily weather grid data on temperature and rainfall from MeteoSuisse (Frei, 2014). The data, therefore, vary cross-sectionally (farms) and temporally (years). All data is cleaned for potential outliers before estimation (see Möhring et al., 2019). See Table 1 for summary statistics of all variables used, Fig. A1 for a map of the distribution of sample farms in Switzerland, and Figs. A2–A4 for histograms of extreme heat days above 34 °C, as well as farmers' insecticide use.

The table reports arithmetic means (mean), standard deviations (sd), minimum (min), and maximum (max) values of farm-year observations of all variables from 2009 to 2018. The sample size is N = 276. Note that pesticide use in the above table refers to farm-level pesticide use of insecticides against the Colorado potato beetle in potato production, respectively. Extreme heat-days refers to the degrees maximum daily temperature exceeds the indicated temperature threshold, summed up over all days of the potato growing season (April–August for Swiss potatoes). Temperature and precipitation variables are available on a municipality level, respectively.

3. Results

Summary statistics show that the temperature threshold of 34 °C is, on average, i.e., over all farm-year observations, exceeded by 0.44 degree-days over the whole potato growing season in Switzerland. Insecticide use against the Colorado potato beetle is heterogeneous, ranging from 0.0187 kg to 0.1323 kg of active ingredients and including 113 observations, where no insecticides against the potato beetle were applied. To identify how far these observations are linked and extreme heat causes changes in insecticide use, we look at the results of our regression model.

We find that extreme heat reduces insecticide use. This effect is statistically significant and economically relevant. Each additional extreme heat day above 34 °C (i.e., each additional day in the growing season with daily maximum temperature exceeding 34 °C by one degree) leads to a reduction in insecticide use of 11.5% (in kilogram of active ingredients, compared to mean insecticide use). The estimated effect size increases for higher critical temperature thresholds and becomes insignificant for thresholds below 34 °C (Fig. 1, Tables 2 and A1). Throughout the analysis, we control for potential effects of precipitation, as well as farm-, farmer- and year-specific effects, such as growing conditions, crop management decisions, farmer behavior, and market and policy conditions over time (Möhring et al., 2020).

We perform extensive robustness checks. First, we check the robustness of estimates to the use of different pesticide use indicators. We thus account for the heterogeneity of used pesticides in terms of potential environmental and health risks (Kudsk et al., 2018; Möhring et al., 2019), e.g., low-toxic products containing Bacillus-thuringiensis are used to control *Leptinotarsa decemlineata*. More specifically, we account for the overall human health,

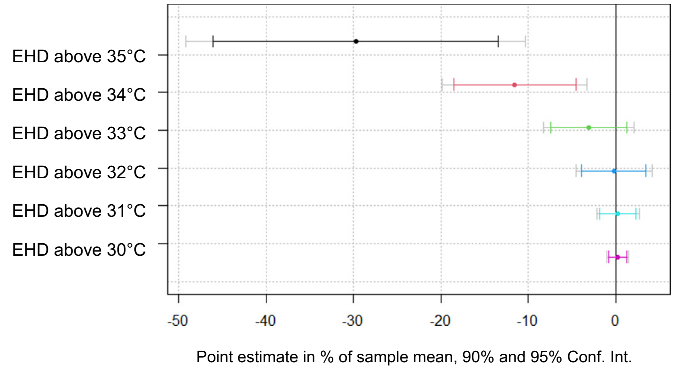

Fig. 1. Effect of extreme heat on insecticide use Horizontal bars show point estimates, as well as 95% and 90% confidence intervals of the marginal effect of extreme heat on insecticide use in Swiss potatoes against the Colorado potato beetle. More specifically, marginal effects show by how much one additional degree and day above the indicated thresholds of daily maximum temperature (i.e. called extreme heat day (EHD)), changes insecticide use of Swiss farmers against potato beetles (in kilograms of active ingredients per hectare). Estimates are expressed in the percentage of mean insecticide use in the sample. Each bar shows estimates of a different model. All models have been separately estimated, only adjusting the temperature threshold for the computation of extreme heat-days. Thresholds have been raised from 30 to 31, 32, 33, 34, and 35 °C for models from bottom to top, respectively. N = 276, and the mean insecticide use in the sample is 0.01873 kg of active ingredients per hectare.

ecotoxicity, and fate load of insecticide use in separate models. We find reductions in potential risk in the same magnitude as quantity reductions, but estimates lack statistical significance (Table 2, Figs. A5–A8).

Second, we check the robustness of our estimates to potential bias from omitted variables (Oster, 2019) and find our results to be very robust. More specifically, for our main model and results (Insecticide use in kilograms of active ingredients and EHDs above 34 and 35 degrees Celsius), we find that selection on unobservables would have to be 3.13 and 3.9 times higher, respectively, than selection on observables to render heat effects zero.

The table shows coefficient estimates of the marginal effect of extreme heat days on insecticide use of Swiss farmers against the Colorado potato beetle across models, as well as standard errors. More specifically, marginal effects show by how much one additional degree and day above the indicated thresholds of daily maximum temperature (i.e., called extreme heat day (EHD)), changes insecticide use of Swiss farmers against potato beetles (in kilograms of active ingredients per hectare). Note that all models are identical except for extreme heat days and pesticide use variables used (Eq. (1)). Rows show models with different temperature thresholds for the extreme heat days variables. Columns show models with different pesticide use indicators. Note that fixed farm- and year-level fixed effects are included, and we use standard errors clustered by years. The sample size is N = 276.

Finally, we investigate the potential mechanisms behind insecticide use reductions more closely and compare if they are likely due to heat-induced

Table 1
Summary statistics of all variables used in the analysis.

Variable	Description	Mean	SD	Min	Max
Quantity of active ingredients	Pesticide use per hectare measured by the quantity of active ingredients (kilograms).	0.01869	0.0214	0	0.1323
Load index	Pesticide use per hectare measured by the load index (Kudsk et al., 2018).	8.9748	11.9584	0	59.6852
Ecotoxicity load	Pesticide use per hectare measured by the Ecotoxicity Load (Kudsk et al., 2018).	8.6685	10.8536	0	23.8208
Fate load	Pesticide use per hectare measured by the Fate Load (Kudsk et al., 2018).	0.0494	0.0691	0	0.5579
Health load	Pesticide use per hectare measured by the Health Load (Kudsk et al., 2018).	0.0642	0.1657	0	1.4786
EHD30	Extreme heat-days above threshold of 30 °C.	16.8245	22.0408	0.0927	173.0297
EHD31	Extreme heat-days above threshold of 31 °C.	8.2041	11.8553	0	76.2389
EHD32	Extreme heat-days above threshold of 32 °C.	3.4830	6.3757	0	38.1885
EHD33	Extreme heat-days above threshold of 33 °C.	1.3015	3.3418	0	23.3692
EHD34	Extreme heat-days above threshold of 34 °C.	0.4376	1.4154	0	12.3018
EHD35	Extreme heat-days above threshold of 35 °C.	0.1132	0.4455	0	3.5128
Precipitation	Yearly sum of precipitation (l/m^2).	545.6967	165.5554	250.7844	1354.606

Table 2
Coefficient estimates of the effect of extreme heat days (EHD) on pesticide use across all models (different temperature thresholds and pesticide use indicators).

Model	QA	Load Index	Ecotoxicity Load	Fate Load	Health Load
EHD above 35° C	−0,00555 (0,00185)	−0,08359 (274177)	−0,29,467 (263565)	0,00032 (0,01648)	−0,02099 (0,01856)
EHD above 34 °C	−0,00215 (0,00079)	−0,79,713 (0,66,833)	−0,8201 (0,66,103)	−0,00301 (0,0041)	−0,01402 (0,00682)
EHD above 33° C	−0,00057 (0,00049)	−0,12,968 (0,49,955)	−0,14,004 (0,49,732)	0,00074 (0,00342)	−0,00438 (0,00416)
EHD above 32° C	−4,00E−05 (0,00041)	−0,01608 (0,31,585)	−0,03799 (0,30,621)	0,00306 (0,00318)	0,00225 (0,00489)
EHD above 31° C	5,00E-05 (0,00023)	0,02905 (0,1373)	0,00152 (0,13,212)	0,00357 (0,00193)	0,00268 (0,0033)
EHD above 30° C	4,00E-05 (0,00012)	0,00723 (0,06149)	-0,01317 (0,06045)	0,00228 (0,00099)	0,00136 (0,00179)

reductions in insect populations (rendering treatments unnecessary) or heat-induced reductions in crop yields (rendering treatments unprofitable). We find that after considering the realized heat-induced yield losses, insecticide application would still be economically profitable for the great majority of plots, already at minimal infestation rates of under one larvae per plant (see Fig. 2 below). Our results reflect that, although control costs can be up to 200 CHF per hectare in Switzerland, the costs of insecticide applications are still very low compared to the high per-hectare revenues in potato production (Mouron et al., 2013). We thus conclude that potential heat-induced adjustments in insecticide use rather stem from reductions in pest pressure than economic considerations in our sample.

4. Discussion

It has previously been shown in experiments and models that pressure from important pests (e.g., in potatoes) may grow with warmer temperatures but drastically declines above certain temperature thresholds (Logan et al., 1985; Zhang et al., 2015). Such extreme heat effects on insects can often not be attributed to single mechanisms but rather to a combination of heat damages, as well as molecular, biochemical, and physiological changes in insect populations (see Ma et al., 2021 for an overview and discussion). Thus, while insecticide use, ceteris paribus, might increase in a warming climate, accompanying increases in extreme heat events could partially counteract this development. Ma et al. (2021) highlight the global relevance of the effects of extreme heat on insect populations and the need for further research on this topic.

However, experimental results on the effect of extreme heat on insect populations cannot directly be transferred to insecticide use levels, as they do not consider farmer behavior and their potentially substantial adjustments in management decisions following extreme heat, e.g., due to lower expected crop yields (Schlenker and Roberts, 2009; Alyokhin et al., 2015).

To analyze the effect of extreme temperatures on insecticide use under real field conditions, we combine data on observed, field-level pesticide use decisions of farmers against the Colorado potato beetle and on weather

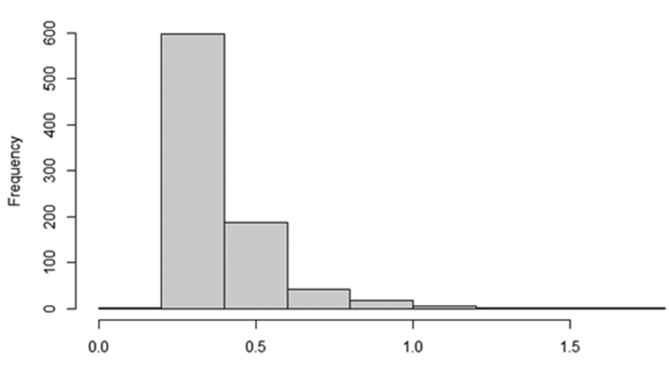

Fig. 2. Histogram of minimal infestation rates with potato beetles necessary to cross economic thresholds for insecticide applications (per plot) The graph shows minimum infestation levels of potato plants with Colorado potato beetles necessary in order to economically justify insecticide applications (crossing economic application thresholds) per field. N = 886.

conditions, and thus account for potential adaptation responses both of the ecosystem and the farmers' pest management behavior in our analysis.

We empirically show that extreme heat can lead to substantial reductions in farmers' insecticide use and quantify these effects under real field conditions. We find that extreme heat above a temperature threshold of 34 °C leads to large and statistically significant reductions of 11.5% of insecticide use (per additional degree and day the temperature threshold is crossed in the growing season) against the Colorado potato beetle in Swiss potato production. For lower temperature thresholds, no effects are found. This reduction translates into reduced control costs for farmers, as well as reduced environmental and health risks from insecticide use. Assuming linear pest control expenditures, an additional degree and day above 34 °C would, for example, imply cost reductions of up to 23 CHF/ha. Our results are robust to potential omitted variable bias, and we find reductions in the same magnitude as for the quantity-based indicator when using pesticide indicators based on their environmental and human health risks. However, results for the latter are statistically not significant, which might be due to the great heterogeneity of pesticide properties, which are usually not linked to the farmers' choices of products (Möhring et al., 2019).

We further investigate potential underlying mechanisms of the farmers' decisions and find strong evidence that reductions in insecticide use are mainly driven by heat-induced reductions in pest pressure. We argue that this is also due to low prices of insecticides compared to expected revenues in potato production and resulting low economic application thresholds.

5. Conclusion

We here present the first study, which empirically analyses farmers' insecticide use decisions under real field conditions in response to extreme heat. Our results show that extreme heat plays an important role for farmers' insecticide use levels, also in regions with a relatively cool climate and accounting for farmers' adaption decisions.

Our study confirms that accounting for extreme temperature is essential for understanding the effects of climate and climate change on pesticide use. Increasing extreme heat events could (partially) counteract potential effects of increases in average surface temperature on insecticide use (Deutsch et al., 2018) and should be considered in projections on future pesticide use. Reliable projections of future pesticide use will be key to designing suitable tools and policies for sustainable pest management and making agriculture ready for a warming and more extreme climate (Möhring et al., 2020).

Our empirical analysis focuses on insecticide use against the Colorado potato beetle, which is an important global pest, causing great economic damages and further expanding under climate change – and therefore an emblematic case study. Our findings on pesticide use decisions contribute to current policy discussions in Switzerland and surrounding countries in the European Union (Finger, 2021; Möhring et al., 2020).

Implications of our study go beyond empirical results for the chosen case study: The growing evidence on the broad potential effects of extreme heat on insect populations highlights the need for further research in this area (Ma et al., 2021). Additional (large-scale) empirical investigations for different pests, crops, and climatic zones are therefore needed to quantify the impacts of extreme heat on insecticide use and to account for them in predictions on pesticide use in a warming climate. It will be key to quantify such effects under real field conditions, i.e., accounting for farmer behavior and adaption decisions to extreme weather conditions. We here show how to combine methods to assess and improve our knowledge on the combined major challenges of reducing pesticide risks and coping with the effects of climate change on agriculture while accounting for human behavior.

However, leveraging studies on a larger scale requires long-term, precise data on farmers' decisions and their economic, environmental, and health impacts (Möhring et al., 2020; Tang et al., 2021). Especially the access to precise and reliable pesticide use data is currently limited by most authorities and therefore needs to be reformed in order to allow for a large-scale evaluation of pesticide use decisions under climate change (Mesnage et al., 2021).

CRediT authorship contribution statement

Niklas Möhring: Conceptualization, Methodology, Software, Methodology, Formal analysis, Writing, Visualization, Supervision **Robert Finger:** Conceptualization, Writing **Tobias Dalhaus:** Conceptualization, Methodology, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152043.

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