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Glyphosate ban will have economic impacts on European agriculture but effects are heterogenous and uncertain

Robert Finger [1✉], Niklas Möhring [2] & Per Kudsk [3]

Glyphosate is the most widely used pesticide in Europe. However, due to its potential effects on human health, its renewal is currently under discussion in European policy. Here, we synthesize the existing evidence on potential farm-level economic impacts of a potential glyphosate ban in European agriculture using a literature review. We identified 19 studies published until 2022. We find that where glyphosate is currently used (30% and 50% of the acreage with annual and perennial tree crops respectively), such a ban can have large economic impacts. However, the range of impacts reported in the literature is substantial. Economic losses arising from a glyphosate ban estimated in peer reviewed studies range from 3 Euro/hectare in silage maize to up to 553 Euro/hectare in grapevine production. While potential losses are largest, in absolute terms (in Euro/hectare), for high-value perennial crops such as fruits and grapevines losses are similar in perennial and arable crops if expressed in relative terms (i.e. in % of per hectare profits). We currently lack assessments of economic implications of a glyphosate ban for most countries and farming systems. Thus, the overall economic implications at the European level are largely unknown.

[1] ETH Zürich, Zürich, Switzerland. [2] Niklas Möhring, Business Economics Group, Wageningen University and Research, Wageningen, The Netherlands. [3] Per Kudsk, Aarhus University, Slagelse, Denmark. ✉email: rofinger@ethz.ch

Efficient pest and weed management are crucial for global food security[1]. However, the current reliance on pesticides in pest management implies negative effects for the environment and human health (e.g.[2,3]). Thus, pesticide risk reduction is a priority in agricultural and environmental policies. Ambitious pesticide policy reduction targets have been set in Europe as well as globally in the Post-2020 Global Biodiversity Framework[4–8].

Glyphosate is the most widely used active ingredient in Europe (and worldwide) (e.g.[9,10]) in terms of quantity. Its global use in agriculture was 746,580 t in 2014, representing 18% and 92% of all pesticide and herbicide use globally, respectively[9]. In Europe, at large, glyphosate represents one third of all herbicides used[9]. Glyphosate is used for a wide range of applications in Europe, i.e. for weed control in annual and perennial crops, termination of cover crops, termination of temporary grassland and renewing permanent grassland, crop desiccation as well as a harvest aid[9]. Glyphosate is also increasingly used pre-emergence, as part of an anti-resistance strategy. This has become necessary due to the increasing problems with herbicide resistance in European cropping systems to other herbicide active ingredients and the lack of new modes of actions[11–13]. Note that there are no genetically modified glyphosate tolerant crops grown in Europe and thus the use pattern of glyphosate in Europe is different compared to large parts of global agriculture[14,15].

Potential direct and indirect effects of glyphosate use on human health and the environment have triggered a debate to fully ban glyphosate use (see [16]). Overviews on potential effects of glyphosate on human health and the environment are given, for example, by Gandhi et al.[17] Maggi et al.[18] and Van Bruggen et al.[19]. Impacts of a glyphosate ban on the environment and human health depend on the alternative strategies used, especially on whether these are chemical or non-chemical (see also [10]). Major discussions on a glyphosate ban in Europe started in 2015, when the International Agency on Research on Cancer of the World Health Organization, in an assessment of glyphosate, concluded that the compound was 'probably carcinogenic to humans'[16]. In subsequent assessments, the European Food Safety Authority and the European Chemical Agency concluded that glyphosate could not be classified as a carcinogen (see [16] for details). Yet, based on ongoing debates, the European Commission renewed the approval of glyphosate in 2017 only for additional 5 years (further extended by one additional year in 2022, see e.g.[20]). Independently, several European countries recently announced future bans or massive restrictions on the use of glyphosate (e.g. Austria, Germany, France) (e.g[21–23].). The EU, at large, is expected to decide on the renewal of the approval of glyphosate ultimo 2023[20]. The decision to approve an active substance such as glyphosate is taken at the EU level. However, once an active substance is approved by the EU, each Member State must then separately authorize the use of any product containing glyphosate[16]. See Leonelli[23] for critical reflections on legal and political processes.

Decisions on the renewal of the approval of glyphosate in the EU are mainly guided by potential environmental and human health risks (e.g.[20]). However, economic implications are inevitably relevant in any decision to ban a product that is widely used and has important implications for the design of production systems. Along these lines, EFSA only provides scientific advice, while the European Commission assisted by the Member States remains the risk manager and is required to take a broader range of issues into account. The General Food Law EU legislation (Regulation178/2002), for example, recognizes "…that scientific risk assessment alone cannot always provide all the information on which a risk management decision should be based, and that other factors relevant to the matter under consideration should legitimately be taken into account including societal, economic, traditional, ethical and environmental factors and the feasibility of controls." (Recital 19), as well as the precautionary principle (Article 7[1]).

Here, we provide an overview and synthesis of the existing evidence on potential economic impacts of a glyphosate ban in European agriculture. It is based on a systematic review of the literature including both peer reviewed and non-peer reviewed studies, accounting for a wide range of agricultural systems and countries.

Key starting point for an assessment of economic implications of a glyphosate ban is that in Europe, glyphosate is currently used each year on 30% of annual crops and 50% of perennial tree cropping systems (such as olive groves, vineyards, and fruit orchards)[9]. The use of glyphosate differs largely across countries and cropping systems across Europe. As a result, the share of glyphosate (i.e. products with glyphosate as a main active ingredient) among the total national total herbicide sales in 2017 varied from 20% (Lithuania) to 78% (Greece) among European countries[9]. Such differences in the relevance of glyphosate use are, among others, due to differences in cropping systems, climatic conditions as well as country specific regulation on the uses of glyphosate (e.g. the use for desiccation, i.e. as harvest aid, is not authorized in all countries) (e.g[9].). For areas currently not treated with glyphosate, a ban may, however, also have economic implications, e.g., due to a lost option value for future use.

Where glyphosate is currently used, the possible economic impacts of a ban may stem from a combination of three main effects. These are related to the current mode of use of glyphosate in European cropping systems (e.g[10].). First, alternative strategies for weed control, and termination of cover crops and grassland may be more expensive, implying for example additional costs for machinery, fuel and labor (e.g[24,25].). Second, the adoption of less effective alternatives for weed control e.g. against perennial weeds may cause yield losses due to lower efficacy, i.e. the level of crop protection (e.g[26].). Third, banning glyphosate may cause fundamental and costly shifts in crop management and farming systems. For example, soil tillage practices such as conservation agriculture or other forms of no- or reduced-tillage are often linked to the use of glyphosate (e.g[27].). Moreover, not using glyphosate may potentially require costly adjustments in crop rotations, farming practices and land use, e.g. to allow for mechanical control of perennial weeds in between crops. Thus, a ban of glyphosate would imply opportunity costs (i.e. foregone profits) for many farms.

To identify relevant studies on economic costs of a glyphosate ban in Europe, we use a triangulation of methods (see method section for details). First, we conducted a systematic review of scientific literature, using specific search criteria employed over the databases 'Web of Science' and 'Scopus'. Second, we extended our search to'Google Scholar' to capture also non-peer reviewed literature, also in a large range of other languages than English. Third, we approached a Europe-wide network of experts in integrated pest management to identify any national report on economic implications. We focused on European countries inside and outside the EU. More specifically, a glyphosate ban is also discussed in non-EU countries, and countries (including agricultural systems and policies) in Europe are closely interlinked. Thus, the topic is of relevance for Europe at large. Moreover, European countries share key characteristics of cropping systems, e.g. production without genetically modified glyphosate tolerant crops. Thus, findings from other European countries can also inform the potential implications in the EU (and vice versa).

Results and discussion

We identified 19 studies (published between 2010 and 2022) that assessed economic implications of a glyphosate ban in European countries (Fig. 1). The considered publications are mainly written in English, but we also identified and included studies in Danish, French, German, and Swedish. These studies often cover multiple crops, crop rotations, regions and even multiple countries. Thus, the 19 studies resulted in many individual assessments (e.g. crop-country combinations) of economic impacts of a glyphosate ban (see the Supplementary Table 1 for all details). Ten of these studies are peer-reviewed, nine are not peer-reviewed. The latter are usually reports commissioned by national governments or industry representations.

The identified studies reveal a biased representation of countries, agricultural systems and uses of glyphosate (Fig. 1 and Tables 1, 2). For example, in total, 10 out of 19 studies cover German agriculture (a single study can also cover multiple countries), four studies cover France, two Spain, and one study each covers Italy, Sweden, Denmark, and Austria. We also included four studies covering the United Kingdom (left the EU on January 31, 2020) and one study for Switzerland. Most studies[14] cover either multiple crops, entire crop rotations, entire farms, or the entire agricultural sector of a country. In at least 13 of the studies, wheat was considered explicitly, reflecting its importance as the most widely grown crop in European agriculture. Perennial and minor crops are less frequently considered, e.g. only two studies considered apples, and one study each considered grapevine, olives, and citrus. Most studies focus on pre-sowing and post-harvest weed control. Other economically relevant applications, like the termination of temporary grassland and cover crops, renewing permanent grassland and crop desiccation are not or only rarely explicitly considered in economic assessments. Only few studies (i.e.[27,28]) quantified explicitly the economic implications a ban of glyphosate may have on conservation agricultural practices, concluding that no-or reduced-till practices may be difficult to apply.

Overall, our analysis revealed that important knowledge gaps remain, because most European countries, many highly relevant cropping systems and important uses of glyphosate are not at all, or only rarely, represented in the existing studies on economic implications of a glyphosate ban (Fig. 1). However, a good coverage of different cropping systems and countries would be required to provide a full overview of economic effects of glyphosate use. These effects may potentially be highly heterogeneous, especially along the gradient from Northern to Southern Europe, e.g., due a shorter growing season in the North that limits the opportunities for mechanical weed control between crops.

Tables 1 and 2 summarize key results. We find that the range of economic impacts in absolute terms is substantial in the reviewed studies. Within peer-reviewed studies, for example, the economic implications of a glyphosate ban range from 2–3€/ha (and cropping season) in German silage maize[24] to 12–553€/ha in French vineyards[21]. The latter estimated economic impacts represent between 1%[24] and 1–11%[21] of profit margins in the respective cropping systems.

The wide range of economic implications across studies is due to various reasons. For example, it reflects the large differences in the difficulty of substituting glyphosate across crops and cropping systems. This comprises the availability of substitutes and additional labor and machinery demand, as well as differences in the costs for these required additional inputs across countries. Moreover, crop prices and revenues per hectare differ substantially (e.g. between maize and grapevine), so that small yield

Fig. 1 Distribution of identified studies on the farm-level economic impacts of a glyphosate ban in Europe (considered cropping systems in parentheses). Note: Country abbreviations are as follows: AT – Austria, CH – Switzerland, DE – Germany, DK – Denmark, ES – Spain, FR – France, IT – Italy, SE- Sweden, UK – United Kingdom. The figure is based on www.freeworldmaps.net.

Table 1 Synthesis of the identified studies on the farm-level economic impacts of a glyphosate ban in Europe: peer-reviewed studies.

#	Study name (reference number)	Country	Crop	Estimated impact (in € per hectare (ha) and year)	Method
1	Böcker et al. 2018[36]	Germany	Silage Maize	Profit margins reduced by €1–2/ha.	Detailed spatial explicit bio-economic model.
2	Böcker et al. 2019[32]	Switzerland	Wheat	Median profit reductions 35€/ha-68€/ha (CHF 36/ha to 71/ha).	Detailed spatial explicit bio-economic model.
3	Böcker et al. 2020[24]	Germany	Silage Maize	Profit margins are on average reduced by €2–3/ha.	Detailed spatial explicit bio-economic model.
4	Cook et al. 2010[50]	UK	Wheat, oilseed rape	Up to 553€/ha (£473/ha) in wheat and 450€/ha (£470/ha) in oilseed rape crops.	Interviews, literature review, partial budgeting.
5	Jacquet et al. 2021[21]	France	Grapevine	range from 12€/ha to 553€/ha (250€/ha average, 1–11.5% of the gross operating profit).	Data from 7156 plots, literature review and partial budgeting.
6	Garvert 2013[26]	Germany	Crop rotations in 3 regions of Germany.	Gross margin reductions range from 0€/ha to ca. 150€/ha).	Expert interviews and partial budgeting, potential crop price effects accounted for with multi-product-multi-region model AGRISIM.
7	Pardo & Martínez 2019[27]	Spain	Arable production; Fruit production.	For arable crops ca. 96–102€/ha. For perennial crops 79–120€/ha.	Calculations of cost changes based on one hypothetical arable farm and one hypothetical tree producer.
8	Schulte et al. 2017a[28]	Germany	Crop rotations including rapeseed, winter wheat, maize, winter barley.	Between 10.86 €/ha, and 68.90 €/ha at crop rotation level (average across crops). If a glyphosate ban induces a switch to ploughing, it increases losses by factor 2–3.	Surveys with farmers, expert interviews, partial budgeting.
9	Steinmann et al. 2012[31]	Germany	Arable farms	Losses range from 4.7 €/ha to 12 €/ha.	Survey with farmers, and partial budgeting.
10	Wynn et al. 2014[51]	UK, France, Germany	Wheat, winter barley, oilseed rape	Gross margin reduction (in €/ha) for a) UK, b) FR, c) GER, in Winter wheat: a) −390, b) −361, c) −100 Winter barley: a) −318 b) −259 c) −63) Rapeseed: a) −299 b) −314 c) −133.	Gross margin calculation extrapolated based on national acreages; assumes yield losses and additional costs for substitutes through expert interviews.

Note: Further details are presented in the Supplementary Table 1.

Table 2 Synthesis of the identified studies on the farm-level economic impacts of a glyphosate ban in Europe: non-peer reviewed studies.

#	Study name (reference number)	Country	Crop	Estimated impact (in € per hectare (ha) and year)	Method
11	Anonymous 2017[52]	UK	UK agriculture at large	Ca. 114 €/ha	Literature review, simulation model.
12	Carpentier et al. 2020[30]	France	Arable farms	Between 6.5 and 80€/ha (1.3-16% of profit margin), with below 10 €/ha for majority of area (80%).	Econometric analysis of data from 17,342 parcels, based on propensity score matching to compare users and non-users of glyphosate.
13	ECPA 2017[34]	France, United Kingdom, Germany, Spain, Italy	Wheat, barley, potatoes, sugar beet, rapeseed, peas, citrus, olives, tomatoes, grapes	Wheat: 132–219€/ha (France), 112–293€/ha (Germany), 124–247€/ha (UK); Rapeseed: 120–315€/ha (Germany), 145–289€/ha (UK); Maize 202–324€/ha (Italy), Olives: 75€/ha (Spain); Grapes: 10–30€/ha (Italy), Citrus 626€/ha (Spain).	Extrapolating average losses in productivity, quality and costs from glyphosate substitution based on expert interviews and field trial data.
14	Johansson et al. 2019[37]	Sweden	Different farm types	Losses of 30€ to 149€/ha.	Five representative farm types, literature, partial budgeting.
15	Kehlenbeck et al. 2015[29]	Germany	Apples	Annual costs of not using glyphosate range from 1.118 €/ha to 1.201 €/ha.	Literature review and partial budgeting.
16	Kehlenbeck et al. 2016[53]	Germany (country level)	Five Different crop rotations and different tillage systems	Gross margin reductions range on average between −9 €/ha (i.e. higher profits) and 99€/ha.	Literature review, detailed assumptions on yields, revenues and costs, and partial budgeting, several scenarios.
17	Mitter et al. 2019[33]	Austria	Arable crop production	range from 22€/ha to 163€/ha (8–60% of profit margins).	Integrated modeling approach accounting for land use changes.
18	Petersen et al. 2022[38]	Denmark	Different farm types	Average losses 113 €/ha (range from 33 €/ha to 272 €/ha.	Ten farm types encompassing the current crop distribution, partial budgeting.
19	Schulte et a al. 2017b[35]	Germany	Typical crop rotations	16–48 €/ha.	Economic analysis for 3 exemplary farms.

Note: Further details are presented in the Supplementary Table 1.

losses due to less effective weed control may or may not result in relatively large economic impacts. Finally, the revealed heterogeneity and uncertainty of estimated economic impacts is very large, both, within individual studies and also across studies, e.g. depending on farming systems studied and assessment methods used.

Relevant key patterns emerging from our synthesis (cp. Tables 1, 2 and Supplementary Table 1).

Potential economic losses arising from a glyphosate ban expressed in absolute terms are largest for high-value perennial crops such as fruits and grapevine. For example, losses for French grapevine are in the range of 12–553€/ha[21] and even up to 1201€/ha in German apple production (representing a reduction of profit margins by ca. 20%)[29].

The economic impacts of a glyphosate ban are - in absolute terms (i.e. in €/ha)– lower for arable crops, i.e. are usually below 100 €/ha. For example, Carpentier et al.[30]. show that for French arable farming profit losses range from 6.5 €/ha to 80 €/ha, and Steinmann et al.[31]. find profit reduction in German crop production between 4.7 to 12 €/ha. Along these lines, Schulte et al.[28]. show that for German arable production the crop rotation level impacts range between 10.86 and 68.90 €/ha. Böcker et al.[32] find profit reductions between 35 and 68 €/ha for Swiss wheat, and Mitter et al.[33] find profit reduction in Austrian arable crop production between 22 and 163 €/ha. However, these effects of a glyphosate ban for arable crops are often similarly high in relative terms (i.e. as share of profit margins) as for perennial crops, as total profit margins for many arable crops are often only a few hundred Euros per hectare. For example, Garvert[26] show for German crop production that the maximum reductions of gross margins range between 3% and 27%. A study by ECPA[34] shows gross margin reductions by 10–30% for crops like wheat, oilseed rape and pea in the UK, and 4–37% for wheat, barley, and potato in France (see Supplementary Table 1).

One reason why absolute economic losses are higher in perennial crops is that glyphosate is the main herbicide and often used multiple times per year, while in arable crops glyphosate is used along with other herbicides and often only used once per year and not necessarily every year (e.g.[29]). Moreover, alternative weed control strategies like mechanical methods are often more difficult and costly to implement in perennial crops[21]. In addition, due to high absolute revenues in perennial cropping systems, even small yield losses imply larger absolute revenue reductions.

Moreover, the different methodological approaches used contribute to the large heterogeneity of results, even in similar cropping systems. Many studies used interviews or surveys to elicit knowledge and expectations by farmers and/or plant protection experts. For example, Schulte et al.[35] and Garvert[26] used interviews and surveys with farmers and crop protection experts to assess possible yield losses and cost increases. However, internal, and external validity of sampled experts were often not discussed in detail in the identified studies (cp. Supplementary Table 1). Also combinations of representative data with expert knowledge are widely used. For example, Jacquet et al.[21] assess the micro-economic impact of a glyphosate ban for French wine-producing farms, combining the data from a large national survey on crop practices at field level and comparing the costs of techniques identified for various farms. Böcker et al.[24,32,36] use detailed bio-economic and spatially explicit models that represent farmers choices between hundreds of combinations of different weed management options. They account for different production conditions and weed pressure and assess yield and profit effects arising from the removal of glyphosate from farmers choice set. The studies by Böcker et al.[24,32,36] highlight the need to account for the costs of both direct substitutes for glyphosate (e.g. other herbicides, mechanical weed control), as well as changes in production systems (e.g. pesticide-free or organic production). The studies by Johansson et al.[37] and Petersen et al.[38] underline the relevance of considering a farm-level perspective beyond individual crops. Eighteen studies provide ex-ante assessments, and only one study uses an ex-post analysis, aiming to causally identify the effects of not using glyphosate in a quasi-experimental design: Carpentier et al.[30] use a propensity score matching approach on farm level data to identify effects of glyphosate use on profit margins. Such more complex statistical approaches are, for example, needed to account for self-selection biases, i.e. that farms currently using and not using glyphosate differ structurally. Simple performance comparisons would then be misleading.

The here identified 19 studies often focus on a narrow set of pathways how banning glyphosate affects farms, i.e. mainly costs for weed control and yield effects. The economic implications of banning glyphosate on aspects like tillage systems and labor are rarely addressed, but they may be crucial. For example, accounting for the need to switch from no- or reduced tillage to ploughing following a glyphosate ban can be costly. Schulte et al.[28] show that if farmers must switch from mulch tillage (with glyphosate) to ploughing (without glyphosate), the estimated absolute losses per hectare could increase by factor 2–3. Petersen et al.[38] assume that non-inversion tillage and conservation agriculture would cease in case of a glyphosate ban. Moreover, substituting glyphosate use may require additional labor demand and investments in new machinery. Schulte et al.[35] indicate a 10% increase of labor demand in German crop production. A ban of glyphosate may thus require fundamental adjustments of farm practices and organization (e.g., timing and peaks for labor demand).

Most studies assess implications of a glyphosate ban enforced in short-term. However, taking a longer-term perspective could change economic impacts. For example, this could result in lower negative economic impacts, e.g. because over a period of multiple years farming systems and crop rotations can be adjusted more easily and improved technologies (e.g. precision farming, improved mechanical weed control technologies) can be used and developed further (see [39]). In contrast, potential long-term effects of a build-up of the weed population, and in particular perennial weed species, could increase negative economic impacts for farmers of a glyphosate ban if accounting for dynamic aspects (e.g.[38]). More specifically, glyphosate is increasingly used for the control of weed population resistant to the in-crop herbicides to prevent/overcome that kind of resistance. This is typically done by applying glyphosate prior to crop germination to kill the first flush of weeds (e.g.[38]). Further, a glyphosate ban may have important effects on the provision of other ecosystem services (e.g., biodiversity) with important societal and farm-level implications. For example, there are potential long-term carryovers of pesticide use impacts on biodiversity on the productivity of farms (e.g.[40]). Such spillover effects of a glyphosate ban may thus also have direct economic relevance for farmers but are currently not considered as part of the authorization in the EU. The strength and direction of these effects will strongly depend on the alternative weed management strategies farmers will choose to replace glyphosate use – farmer decision-making in this area thus deserves special attention in future research. A largely open question is also if and how economic losses due to a glyphosate ban would affect markets and crop prices. For example, reduced yields but also shifts in cropping patterns may imply changes in crop prices (see [26]). The aggregated economic relevance of such market feedback mechanisms is currently not well understood.

Our analysis has implications for policy and industry. We find that, where glyphosate is currently used, a ban of glyphosate can have significant economic impacts, at least in the short run. This finding reflects that glyphosate has become an integrated component of many farming systems. Replacing glyphosate will usually require a bundle of measures (e.g. combinations of agronomic and mechanical solutions and a redesign of cropping systems, e.g.[10]), as single substitutes are often less efficient, a scenario described as the many little hammers[41]. Such a transition could be supported by policy through the targeted development of alternative technologies and alternative farming systems (e.g.[42]) as well as strengthening independent advisory services (e.g.[43]).

Policy interventions may also help to reduce trade-offs between regulating glyphosate use and other agri-environmental goals. For example, to avoid negative environmental effects via reduced uptake of non-inversion tillage systems or conservation agriculture. Targeted measures for farmer support can help to develop and promote the widespread adoption of production systems, which allow to combine no or reduced glyphosate use and conservation agricultural practices.

In a scenario where glyphosate use will not be banned, there might be a need for alternative polices to reduce glyphosate use (e.g. to address societal concerns and to decrease overall the reliance on pesticides). Such steps are especially of relevance in European agriculture, which already has an extensive set of policy measures in place that are regularly restructured. For example, in line with targets for a pesticide risk and use reduction laid out in the Farm-to-Fork Strategy of the European Union and the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework. Our results suggest that it may not be easy for all farmers to reduce the reliance on glyphosate in the short term. An adequate policy mix to support such a step may comprise command and control, information-based as well as market-based policies[8]. The latter can comprise agri-environmental payments as well as price markups for not using glyphosate or other herbicides (see e.g.[44]). Taxation of glyphosate can be a viable push strategy to make the use of (non-chemical) substitutes more attractive; and tax revenues can be reinvested in the agricultural sector to support the use of alternative strategies (see [45]). In fact, Bjørnåvold et al.[46] show that European citizens prefer earmarked taxation schemes that lead to a strong reduction in glyphosate use over a ban, especially if this strategy reduces potential food price increases.

The current evidence on the economic effects of a glyphosate ban in Europe is small and very biased towards specific countries and cropping systems. Given the economic, societal, and political relevance of glyphosate use in European agriculture, an effort shall be made to foster rigorous studies on economic impacts of a glyphosate ban that systematically cover most European countries and farming systems, as well as a wide range of uses of glyphosate. To this end, studies using ex-post assessments, i.e. exploiting observed implications between use and non-use of glyphosate in European agriculture (compare e.g.[30]), and studies using ex-ante assessments shall be initiated. Ex-ante assessments are important to reflect that banning glyphosates may require new, currently unobserved (combinations of) farming practices and technologies for weed control. Coherent triangulation of different methods, e.g. combining expert knowledge, farmer surveys and bio-economic models, shall be used to overcome knowledge gaps and avoid biases (see e.g.[47]). Future studies should holistically consider the key enabling role of glyphosate in certain production systems and potential trade-offs from a ban to provide sound policy advice.

Finally, our study focusses on direct farm-level economic impacts of a glyphosate ban in Europe but neglects crucial aspects such as implications for, e.g., human health and the environment, as well as implications for up- and downstream industries. Thus, our study complements other assessments covering these aspects (e.g.[20]), but should not be the sole source for policy decisions on glyphosate.

Methods

To identify relevant studies, we use a triangulation of methods combining a search over peer-reviewed literature, grey literature and expert consultation. We conduct a systematic review[48] using specific search criteria employed over different databases, i.e. 'Web of Science' and 'Scopus', but also Google Scholar to capture grey literature. More specifically, we use combinations of the keywords "glyphosate", "ban", "glyphosate ban", "costs", "losses", "economic impact" and "profit". The resulting primary list of articles was screened for the titles and abstracts to exclude articles, which did not meet our inclusion criteria. More specifically, we excluded studies not stemming from European countries (but not restricted to European Union members) and studies not reporting economic implications of a non-use or ban of glyphosate (e.g. cost increases or profit reductions). We focused on studies assessing implications for farms and farm-level perspectives. Thus, we did not consider studies assessing, for example, implications for up- and downstream industries. We also did not account for any other costs and benefits arising from a glyphosate ban, e.g. changes in environmental and human health impacts. Thus, our study explicitly intends to complement other assessments providing these details.

We performed the initial search procedure in English, German, French, Swedish and Danish. To overcome the limited visibility of grey literature on the subject, i.e. in governmental reports, as well as to identify publications in other languages, we approached experts in 21 European countries via email (in August 2021). The experts were taken from the ENDURE network, a European Research Group focused on integrated plant protection (www.endure-network.eu). We asked them if they are aware of any relevant study for their countries. We received answers from 12 countries and experts. Finally, based on the shortlisted studies, resulting from the systematic review and expert consultations, also a 'snowballing' procedure was employed[49], where the reference list of the shortlisted articles was scrutinized along with an examination of articles that cited the shortlisted articles. For some studies, different versions exist. For example, the study by Jacquet et al. [21]. (English, peer-reviewed) is based on an earlier report (in French, not peer reviewed). In these cases, we opted for the most recent version of the study and referenced earlier versions in the respective table entry. Moreover, studies that did not explicitly report the specific impacts of not using glyphosate but, for example, studied effects of not using any herbicides at all are not considered. We removed one study from our analysis because the paper was retracted (the authors did not reveal funding sources from industry, (see https://ojs.openagrar.de/index.php/Kulturpflanzenjournal/article/view/12364).

From shortlisted studies, we collected key information: the year (of publication and when the study was conducted, if applicable), the country (or countries), the crop and production system (e.g. individual crops or crop rotations and regions considered), the analyzed agronomic practices (which application modes of glyphosate have been considered), the estimated (range of) economic impacts of a ban (or non-use) of glyphosate, the employed methodology for analysis (surveys, expert interviews, partial budgeting, modes, econometric analysis and combinations thereof) and key assumptions (e.g. if substitution to other weed control was considered or not at all), and if the article was peer reviewed (and the respective journal). Moreover, we extracted the funding source, if applicable, to flag potential conflicts of interests underlying the respective studies (see Supplementary Table 1). Note that several studies also present multiple observations. For example, because different countries and/or crops and cropping systems were investigated. We transformed, wherever possible, information on estimated impacts to a per hectare and year basis. For example, for country-wide estimates, we thus divided costs estimates by the acreage of agricultural land and arable land (using the crop acreage indicated in the studies). Whenever indicated in the studies, we also identified the economic costs in relative terms (e.g. relative to the overall profit margin in an agricultural system), or calculated it based on information provided in the studies. Moreover, we documented main features of the study design and results. We transformed all values in Euros per hectare to ensure comparability across different currencies. Exchange rates as of May 2022 were considered. All entries were at least verified by two co-authors. Note that the heterogeneity of underlying analyses (e.g. methods used in identified studies) and reporting of results, as well as the small number of observations, does not allow for a quantitative meta-analysis of existing literature. We thus, provide an overview and synthesis of findings from identified studies.

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Author contributions

R.F. led the study and the writing of the paper. R.F., N.M. and P.K. contributed to the design of the study, collection of studies and discussions of the results. All authors contributed to the writing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Robert Finger.

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