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REVIEW

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Impact assessment of the loss of glyphosate within the EU: a literature review

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Abstract

Following the introduction of glyphosate in 1974, its efficacy against a vast range of weeds and its low price has established it as Europe's most widely used herbicide. However, concerns about possible health and environmental impacts now threaten its continued approval for use. This review considers the contribution of glyphosate to European agriculture and the likely impacts on crop production if it were to be withdrawn. Without glyphosate, EU farmers could experience losses in wheat production of up to 24 Mt (worth €10.5 billion), 10.4 Mt in potatoes (worth €2 billion), and 4.7 Mt in grapes (worth €4.2 billion). Withdrawal of glyphosate would result in an increase in soil tillage, damaging the environment through soil structure degradation, increased risk of soil erosion, reduced soil biodiversity, and increased greenhouse gas emissions of 1.4–3.8 Mt CO_2e per year across the EU through oxidation of organic matter. Increased machinery usage would require 15–44 L more fuel per hectare. Alternative weed control strategies are both less effective and more costly, often requiring additional labour at times of peak demand. They are also less effective at providing lasting control across a broad range of species and are inapplicable to conservation tillage practices.

Keywords: Glyphosate, Weed management, Yield, Production, Wheat, Potatoes, Grape vines

Introduction

Glyphosate is the most frequently used herbicide within the European Union (EU) for weed control in agricultural and non-agricultural situations [3]. It offers systemic control of a broad spectrum of weed species, whilst being effective at a range of growth stages and timings. Its broad-spectrum activity and lack of soil residual activity (>30 days) make it useful for cleaning crop fields between the harvest of one crop and planting of the next (the inter-crop period) or to terminate cover crops prior to next planting [15, 18]. Glyphosate is also used to maintain the areas underneath the rows in vines and orchards to prevent weeds competing with the crop [3].

Due to its non-selective nature, glyphosate can control a wide range of plant species, including both sensitive weed and crop species. The main use of glyphosate in arable crops is in the period between the harvest of one crop and planting of the next, whilst in vines and orchard crops it can be used around the base of the vines and trees, as long as it is not applied to the leaves [8, 20]. Glyphosate is a systemic herbicide that is translocated by the plant from the leaves and other tissues where the spray is applied, throughout the plant, including to the roots [9]. This means that it is highly effective at controlling deep rooted perennial weeds with complex root systems, like some of the rhizomatous grass species (e.g. *Elymus repens*) [33], as well as targeting a range of annual weed species, including those that are resistant to other herbicidal modes of action. In many crop production situations, glyphosate is used as part of an integrated weed management programme that includes cultivation and post-planting selective herbicide usage, as well as crop rotation and timing of planting to minimise the weed burden within the crop and the carryover of weed seed from one crop to the next [18]. It is also a fundamental part of minimum tillage or conservation tillage systems,

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facilitating high levels of weed control with minimal requirements for tillage.

This analysis brings together existing information and aggregates information at the EU-28 level (all countries that were members of the EU in December 2019) on the importance of glyphosate to EU agriculture and the impact of a potential withdrawal of its registration. The overall European picture with some cross-reference to specific examples in individual countries is discussed. Other studies have been published that analyse the impact that the loss of glyphosate would have on agriculture and weed management in countries outside of Europe, such as Mexico [2] and Australia [39].

The key uses of glyphosate examined here are pre-planting or stubble management, pre-emergence, conservation tillage, and orchards and vines. Glyphosate use is widespread due to its broad spectrum of activity and the relative lack of resistance to this herbicide in the EU. There is widespread resistance to many of the more selective herbicide modes of action in key weed species, such as blackgrass (*Alopecurus myosuroides*), leaving limited chemical control opportunities for this highly competitive weed [28]. Glyphosate has a unique mode of action, targeting and inhibiting the 5-enolpyruvyl-3-shikimate phosphate synthase (EPSPS) enzyme which prevents the synthesis of certain folates and amino acids, resulting in plant death [8]. It is therefore an important tool for managing resistance across a range of weed species in the EU, especially when applied in the pre-planting application window, particularly important in winter wheat.

There are a number of potential alternative approaches to weed management that could be implemented if glyphosate were to be withdrawn; however, there are some associated costs [5, 15, 18]. Glyphosate is rarely applied as the sole source of weed control and, in many cases, glyphosate is already being applied in combination with one or more of the alternatives as part of an integrated weed management strategy [26]. Therefore, it is not always a case of making a direct substitution of one for the other. Instead, it might elicit an increase in the intensity or frequency of application of the alternative to try to maintain the same level of weed control. The main alternative weed control approaches are as follows: increase in cultivations (mechanical weed control); thermal or alternative weeding; use of selective herbicides (generally applied as mixtures to increase the weed spectrum controlled); and significant changes to crop rotations, sometimes including pasture for one or more years [15, 18].

At present, if glyphosate does not provide adequate control of weeds, chemical companies will compensate farmers financially (if used as described on the product label and an investigation reveals no other controllable factor is responsible) (Bayer, personal communication, 2020). If an alternative method fails to provide adequate weed control, the farmer must absorb the loss of production and incurred costs, increasing business risk [17, 22]. Some of the alternatives may provide a short-term benefit, but result in increased problems in the future, at the expense of the farmer. On most farms, gross margins are already tight and the ability of farmers to absorb extra costs or reduced income is very low. Therefore, any changes in weed control strategy that increase the risks associated with crop production could cause significant damage to the long-term financial viability of farms.

The aim of this review is to determine the value and effectiveness of glyphosate in European agriculture, through the collation of existing studies completed across the EU, in order to understand the socio-economic and environmental implications associated with its potential withdrawal from the market.

Methodology

This review focused on the value and effectiveness of glyphosate use in Europe by collating, analysing, and summarising thirty-two existing socio-economic studies across eight countries and extrapolating the results to a wider European perspective. When searching for studies we focused on identifying studies that had evaluated the impact of glyphosate in at least one of the eight core countries, i.e. France, Hungary, the Netherlands, Sweden, Germany, Italy, Poland, and the United Kingdom (UK). These countries were chosen due to their positions as major crop-producing countries and their significant contributions to total European production.

These studies were produced by a variety of agricultural companies, consultancy groups, and research institutions, such as the European Innovation Partnership and the non-governmental organisation Pesticide Action Network, and were presented in reports available online or in published, peer-reviewed scientific articles. Some studies were funded by agrochemical companies whilst others were produced independently. The studies included had each conducted a socio-economic impact assessment for either the EU or for one of the eight identified countries.

The assessed papers covered several crops which differed between reports and nations; however, for wheat, potatoes, and grape vines (table and wine) multiple sources of data were available. The analysis therefore focused on these key crops and excluded crops where only more limited data were available. As of 2015, EU (including Great Britain) farms covered 173 million hectares (Mha) of Europe [12]. Of the total agricultural land area in the EU, cereal grains cover the largest area, followed by orchards and vegetables. FAO (2020) data show that the main cereal grains (wheat, barley, and maize) covered 46.6 Mha in 2018, with yields averaging 5.4 tonnes per hectare (t ha^{-1}) for wheat, 4.6 t ha^{-1} for barley, and 6.8 t ha^{-1} for maize. Orchard and vine production, in particular vines for both table grapes and wine production, covered a total of 27.2 Mha of the EU agricultural land, with grapes occupying 3.3 Mha and yielding on average 7.1 t ha^{-1}. The main vegetable production areas produced potatoes, carrots, and tomatoes, which covered a total of 2.1 Mha, with potatoes occupying the largest area at 1.7 Mha and yielding on average 31.1 t ha^{-1}.

The thirty-two studies provided a consensus on the potential implications of the withdrawal of glyphosate on EU agriculture in terms of total productivity and cost of production at the farm level, and the wider implications of these impacts on the economy and trade. There were nine studies reviewed which covered France, nine for Germany, three for Italy, two for Poland, two for the UK, five for the Netherlands, one for Sweden, and one for Hungary. Nine studies were reviews at an EU level. These studies had a range of different foci, from assessing the uptake and cost of integrated pest management (IPM) (including weeds), and reviewing the availability of alternative weed control strategies, to directly assessing the economic impact of a withdrawal of glyphosate. These studies covered the EU as a whole or analysed specific countries to provide an overview for the whole of the EU.

This review evaluates the findings and conclusions gleaned from each study. The economic costs given here were based on aggregation of estimates provided by the studies and consideration of the costs associated with the loss of glyphosate.

In a previous unpublished comparative assessment, ADAS assessed the practicality and efficacy of alternatives to glyphosate for weed control, and the information gathered therein was also used for this review.

Results

Yield and production impact

Two out of the nine EU-wide studies looked at the potential yield impacts on EU crop production in the absence of glyphosate. A study carried out by Noleppa & Cartsburg [29] compared 2,318 yield measurement studies, based on glyphosate applications and alternative methods of weed control across the globe. The results show that when glyphosate is used to control weeds, compared with other weed management practices, it delivers a yield advantage of approximately 5.8% in maize, but no significant advantage in oil or protein crops. Overall, the study concluded that applying glyphosate, on average, leads to a positive yield impact when compared to alternative weed control methods, such as mechanical and thermal weed control.

The consultants Steward Redqueen [37] calculated yield impacts on a short-term basis within the EU, based on data from industry experts. Glyphosate was found to be most beneficial for the cultivation of oilseed rape, barley, wheat, and maize. In the absence of glyphosate, a yield reduction of 7–14% could be expected for maize, a yield reduction of 8–18% could be expected for wheat, a yield reduction of 8–19% could be expected for barley, and a yield reduction of 8–22% could be expected in oilseed rape. Yield reductions were based on reduced weed control efficacy delivered by alternative methods compared with glyphosate. Reduced efficacy would reduce yield through increased weed competition, but also by acting as a 'green bridge' to spread diseases, such as ergot (*Claviceps purpurea*), resulting in decreased crop quality.

Using data from across the eight country-level studies, this review forecast that in the absence of glyphosate at the EU level, wheat yields would decline by between 7 and 30% and potatoes by 5 and 20%, whilst in vines (defined herein as table and wine grapes) the yield reductions range from 1–3% in Italy to 12–20% in France.

Scaling the individual country assessments up to the EU level projected the following impacts on production (Table 1).

Wheat

Wheat, and other cereals, would see the largest impacts on production following the loss of glyphosate, with wheat decreasing by 11–24 million tonnes (Mt) and barley by 4–10 Mt across the five EU countries assessed by Steward Redqueen [37] (France, UK, Germany, Spain, and Italy). The country-level studies indicated a 7–30% reduction in wheat yields, which at the EU-28 level would equate to losses of between 9.7 and 41.4 Mt of wheat from a current EU wheat production level of 138 Mt.

Table 1 Predicted impact of glyphosate withdrawal on total EU-28 production of wheat, potatoes, and vines

	EU-28 total production (Mt)	Predicted decrease in production without glyphosate (%)
Wheat	138	30
Potatoes	52	20
Vines	23	20

Estimated output changes in production of main crops with the EU-28 as a result of a glyphosate withdrawal using the collated estimates from the EU studies assessed. 'EU-28 total production' shows production data for 2018 sourced from [14], at the time of the study the UK was still part of the EU

Potatoes

Using data from the country-level studies, this review calculated that potato yields would decline by 5–20%, which, when scaled up to EU production, equates to losses of 2.6–10.4 Mt. Steward Redqueen [37] calculated that potatoes would see a decrease in production of 1–1.2 Mt per year across the five EU countries.

Vines

In the country-level assessments, the pattern of impact contrasted between the Italian data [1], forecasting 1–3% reductions in yield, and the French data, (Steward Redqueen [37], IPSOS [19], and Envilys [11]) which forecasted yield losses of 12–20%. Extrapolating a 3% reduction across the EU-28-level grape area would lead to losses in grape production of 700,000 tonnes, whilst a 20% reduction in production would equate to 4.7 Mt of lost production. Calculations by Steward Redqueen [37] indicate that a reduction of 0.5–1 Mt per year would be expected for vines across the five EU countries they assessed.

Economic impact

This review found a consensus that withdrawal of glyphosate would substantially increase costs to the farmer (Table 2). These costs would arise through the need for additional fuel for increased cultivations and additional labour (as cultivations take longer than spraying) and, in situations where conservation tillage has been adopted, potentially require the purchase of new cultivation equipment that was previously unnecessary.

Wheat

The best data for increases in cost of production were presented for wheat, with estimates of losses ranging from €27 ha^{-1} to €134 ha^{-1} through additional fuel and labour costs [21]. Assuming these cost increases are applied across the whole of the EU wheat area of 25.4 Mha, we calculated an increase in production costs of €690–3,400 million. In addition, a subsequent 7–30% reduction in production, at a value of €171 per tonne, would equate to a €1.6–7.1 billion reduction in the value of EU wheat production. Together it was calculated that in the absence of glyphosate, the cost to the wheat sector could be up to €10.5 billion in increased costs and lost revenue, assuming that crop areas were maintained.

Table 2 Cost of glyphosate withdrawal on wheat, potato, and vine sectors within the EU-28 area

		Wheat	Potatoes	Vines
Base				
EU-28 area	Mha	25.4	1.7	3.3
EU-28 total production	Mt	138	52	23
Average price (2018)	€/t	171	170	741
No glyphosate				
Reduction in production	Mt	41.4	10.4	4.7
Increased costs	€M	3404	190	870
Reduction in value	€M	7100	1770	350
Total impact loss of glyphosate	€M	10500	1960	4220

Calculated based on aggregated data from multiple studies across the EU member states and combined with 2018 data from [14] for the EU-28 baseline data. Results presented as a percentage reduction compared to baseline

Potatoes

Cultivation is already an essential part of crop production in the potato sector, with fields typically cultivated to depth before bed or ridge formation and planting. Therefore, there are limited additional opportunities for using pre-planting cultivations to provide additional weed control above what is already done. Ref. [25] indicated that a loss of glyphosate could reduce gross margins by between €130 ha^{-1} and €343 ha^{-1}. Reductions of €130 ha^{-1} include increased costs of alternative herbicides or alternative mechanical practices, with reductions up to €343 ha^{-1} also include yield losses due to poor weed control in the absence of glyphosate. A reduction in production of 5–20% at a price of €170 per tonne (2018 value) would reduce the monetary value of the sector by €440–1,770 million.

Vines (table and wine grapes)

In one Italian study [1], it was estimated that a loss of glyphosate would increase the cost of weed management in vines by €125–263 ha^{-1}. If these costs were applied across the whole of the EU vine area (3.3 Mha) it would equate to an increase in costs of €413–870 million. In addition, reduction in production of 3–20% at an average value of €714 per tonne would equate to an average loss of revenue of €500–3,350 million. It should be noted that the value of grapes for wine making in particular is highly variable depending on variety and location, meaning that these estimates are subject to large amounts of local variability. In total, the withdrawal of glyphosate could cost the EU vine sector up to €4.2 billion in increased costs and lost revenue.

Societal impact

It was recognised across both the country specific studies and the broader EU studies that the withdrawal of glyphosate would have societal, as well as financial, impacts on farmers. There was a consensus across all the studies that it would take more time to manage weeds in the absence of glyphosate. The additional labour requirements would need to be met either through the increased cost of employing additional staff to complete the tasks, or through the farmer themselves working extra hours to ensure that the tasks were completed at the appropriate time within the season. The persistent shortage of agricultural labour in many countries (e.g. the UK) has been exacerbated by the COVID19 pandemic, and it is questionable whether increased labour needs can be met over the short term [16]. Scheduling of work during peak times on farm would also become increasingly difficult with many operations requiring attention simultaneously.

INRA [17] reported that additional costs associated with increased tillage under a glyphosate withdrawal scenario were variable depending on the cultivation methods used previously. Those previously using a no-tillage, direct-drilling approach would incur the highest additional costs at an average of €102.86 ha^{-1}, whereas those previously operating under conservation tillage could expect between €15.26 and €35.74 ha^{-1} in extra costs. The largest proportion of these costs is related to machinery. Thus, farmers already engaging in conventional tillage would be subjected to the lowest additional costs, approximately €10.39 ha^{-1}, due to already having the necessary equipment available.

Moss [28] found that compared to herbicides, mechanical alternatives are often more complex and time consuming to manage and are less effective. For example, tillage prior to cereal drilling was only 69% effective on average at controlling blackgrass. Mechanical alternatives are also more variable in effectiveness, more labour intensive, more expensive, and often show little visible evidence of success. This implies that farmers would have less time to spend on other operations of the farm, and receive reduced revenues, potentially making farming less profitable, especially for smaller holdings. Mechanical alternatives also lead to reductions in soil organic matter, sequestered carbon, ground cover and habitats for soil- and surface-dwelling organisms, as well as increases in water runoff, soil erosion and soil compaction.

Steward Redqueen [37] found that production of key crops (potatoes, barley, wheat, sugar beet, oilseed rape, maize and grapes) accounts for about 26% of jobs in arable agriculture across the five countries assessed (France, UK, Germany, Spain and Italy), and therefore, assuming a similar distribution in other member states, this would equate to 9.2 million jobs in all of the EU. They also found that glyphosate influences the economic viability of the cultivation of certain crops, ranging from 10–30% extra revenue required for barley, wheat, sugar beet and maize to 20–50% increased revenue required for oilseed rape, grapes, and potatoes. Glyphosate withdrawal could therefore threaten the security of jobs related to production of these crops, as lower yields and higher production costs could result in reduced financial viability of farms without significant price increases for these commodities, which are unlikely to be achieved.

When evaluating the successes and failures of integrated weed management on farms, the EPI-Agri [10] study found that, although some alternatives such as changing cropping systems for non-chemical weed management were effective, negative societal impacts could restrict their uptake. The study found that adapting these alternative tools can sometimes come at great cost to the farmer. Interactions and potential trade-offs with other pests and diseases, nutrient management and value chain issues also need to be considered when changing to a non-chemical weed management system.

Environmental impact

Environmental impact was considered by three of the EU-level studies and a number of the country-level studies. Aspects that were considered included the impacts of switching to alternative approaches on climate change (predominantly through an increased requirement for fuel compared to spray applications), and the impact of changing cultivation practices on soil health, in terms of biodiversity and erosion risk.

Many of the studies cited concerns that the loss of glyphosate would lead to reductions in conservation tillage practices. Currently across Europe there is a trend towards reducing cultivation depth, frequency, and intensity which reduces the cost of production, increases soil organic matter content and health over time, and protects the soil surface from wind and rain erosion, reducing losses of topsoil. However, conservation tillage practices are heavily reliant on the use of glyphosate in the period between crops to establish a weed-free seed bed or terminate a cover crop before planting the following crop. In the absence of glyphosate, weed control would become increasingly challenging if these production systems were maintained. Instead, it is anticipated that the land that is currently managed under conservation tillage will need to revert to a more conventional tillage approach to manage weeds, which will make it challenging to maintain positive financial gross margins on farms for a range of crops. In 2016 it was estimated that about 20% of the EU agricultural area (or about 20 Mha) was managed using conservation tillage practices [13]. More recent data on the current area are limited, but indications are that the area is increasing rather than decreasing. Thus, the loss of glyphosate would have a significant impact on at least a fifth of the EU crop area, with the associated decline in conservation agriculture being likely to increase soil erosion. Conversely, for every hectare converted to conservation agriculture, there is an opportunity to increase carbon removals from the atmosphere via sequestration.

Climate change

When assessing the impact of a switch from glyphosate to alternative methods of weed control, the studies tended to focus on the fact that the increased intensification of cultivation activities would increase the fuel usage per hectare which would ultimately lead to increased carbon dioxide released into the atmosphere.

To assess the impacts of a glyphosate withdrawal, Noleppa & Cartsburg [29] used a case study based on an arable farm in Germany. They applied an 'average' saving of more than 15 L ha^{-1} of diesel and 50 kg CO_2e yr^{-1} to all German arable crop land with reduced tillage. If similar assumptions were applied to the estimated area of EU production under conservation tillage, this would equate to an increase of up to 1.4 Mt CO_2e emissions yr^{-1}. This principle is supported by Brookes et al., [4]. Additional emissions would also be expected from areas of land that are already managed with conventional tillage practices, with emissions increasing further where these practices must be increased and intensified to improve weed control in the absence of glyphosate.

None of the reviewed studies considered the impact of the increase in soil cultivation on the loss of carbon from the soil, nor did they assess the increase in soil compaction due to increased direct rain impacts and more tractor traffic. Kertész & Madarász [23] calculated that conservation tillage needs, on average, 44.2 L ha^{-1} less fuel per year than conventional tillage (equivalent to 134 kg CO_2e ha^{-1} yr^{-1}) and is also able to sequester carbon, as well as reduce oxidation of existing soil carbon, equating to a potential carbon saving of 2.85 t CO_2e ha^{-1} yr^{-1}. When scaled up to 28 Mha of land under conservation tillage, this is the equivalent of 80 Mt CO_2e yr^{-1} that could be emitted if deep cultivations were resumed, plus another 3.8 Mt CO_2e yr^{-1} from additional fuel usage. Eighty Mt CO_2e yr^{-1} is just shy of three times the emissions from the city of London in 2019 [7].

Biodiversity

Most of the studies concluded that the negative impacts of a withdrawal of glyphosate on land managed under conservation tillage would result in an overall negative impact on soil biodiversity. Rodriguez [34] identified that conservation tillage is highly beneficial to the improvement of biodiversity on farms and that without glyphosate this becomes impossible to maintain. The study states that the use of zero tillage systems avoids disrupting the biological activity of the soil and promotes increases in surface cover and soil organic matter and in air exchange, which provides food and a more suitable habitat for insects and other species. A switch to mechanical weed control could decrease populations of earthworms and other soil-dwelling species. A study by Pesticide Action Network Europe (PAN) [31] had previously claimed that glyphosate-based herbicides affect the reproduction of earthworms and cause a dramatic decline in populations; however, in response Moss [28] noted that this assertion failed to acknowledge that reduced tillage and direct drilling, which is nearly always associated with glyphosate use, has been shown to increase worm populations relative to more aggressive tillage practices. In the UK, it was found that deep tillage used in organic systems reduced earthworm populations and that 'organic matter management did not mitigate tillage impacts' [38]. Adding weight to this, Noleppa & Cartsburg [29] found that no-till cultivation can lead to an increased level of soil biological activity, with increased microflora, earthworm, and even bird populations compared to areas subjected to regular ploughing.

A survey conducted by the French DEPHY network [18] asked farmers about the use of glyphosate for improving on-farm biodiversity. The results highlighted that one of the key uses of glyphosate is for the destruction of cover crops, which carpet and protect the soil surface between the main crops in the rotation. Cover crops also serve as additional habitat and food sources for insects and birds during periods when the ground might otherwise be bare and thereby increase biodiversity. The farmers surveyed considered that the loss of glyphosate would make the planting, and more importantly, the destruction of cover crops uneconomic [34]. As a result, there is a risk that the use of cover crops could be negatively impacted in some crop rotations and would need to be replaced with increased cultivations and bare soils between crops, leading to detrimental impacts on biodiversity.

The focus group in the EPI-Agri [10] study evaluated the potential benefits of non-chemical weed control on biodiversity. The study found that it is not always in the best interests of biodiversity to eradicate all weeds in a crop, as the presence of a diverse weed flora can provide other ecosystem services in addition to food production. Weeds can provide food and shelter to biota, including insects that serve as pollinators or natural enemies. Insects in turn act as a food source for birds. The rooting diversity of different weeds also has positive impacts on soil biodiversity. However, they found the resistance to adoption of non-chemical methods stems mainly from farmers' economic considerations which generally focus on the short term. Ecologically based, non-chemical weed management strategies are associated with higher costs and labour requirements in the short term, but greater environmental benefits in the long term (including combatting herbicide resistance and environmental health benefits). They concluded that persuading farmers to adopt non-chemical weed control in the absence of payments to compensate for the short-term revenue reduction requires that long-term benefits are clearly communicated and understood.

Soil health

According to the European Environmental Agency (EEA) [24], about 130 Mha of land in the EU (equivalent to the combined surface area of France, Germany, Italy, and Portugal) suffers from soil erosion caused by rainfall and flooding. Conservation tillage is an important method for minimising the risk of soil erosion, and therefore, a loss of this tool will lead to an increasing proportion of the EU agricultural area being managed using conventional tillage approaches with a subsequently increased risk of soil erosion. Soil compaction is not addressed in this report, but is important to increase water infiltration rates, air exchange flux, and water retention in no-tillage systems [24].

The Noleppa & Cartsburg [29] study found that, without glyphosate, increased tillage would have to be practised on land that would otherwise been under conservation practices. The study highlighted that greater soil moisture retention, increased water infiltration, reduced soil compaction, improved soil tilth, increased surface water quality, reduced soil erosion, and lower nutrient runoffs are associated with conservation agriculture. Conservation tillage systems generally increase soil organic carbon over time, increased levels of organic carbon in the surface layer are beneficial for soil structure, soil biological activity and biodiversity, and seedling emergence. Therefore, moving away from a no-till or reduced tillage practice can have negative consequences for soil health.

Analysis and discussion

Many alternative control options to glyphosate are available, including increased cultivation, thermal weeding, and combinations of selective herbicides. Whilst these alternatives can provide varying levels of weed control, when used alone they are generally less effective at weed control than glyphosate [15]. Poorer weed control enables weeds to compete more with crops, thereby reducing yields. Furthermore, the costs of diminished levels of weed control are higher as farmers must invest more time and fuel into weed management, with selective herbicide alternatives requiring mixtures applied at full rates to reach the same efficacy as glyphosate [15].

It is estimated that, in the absence of glyphosate, the total production of wheat at the EU-28 level could decline by up to 24 Mt, potatoes by 10.4 Mt, and vines by 4.7 Mt. The combination of reduced revenue and increased cost of production is expected to cost the EU wheat sector up to €10.5 billion, the potato sector just under €2 billion and the vine sector (table and wine growing grapes) up to €4.2 billion.

Yield losses and increased farm level-costs will affect the global competitiveness of EU agriculture, the ability of the EU to be self-sufficient in food, and the trade balance contributions of agricultural commodities that are exported. The EU is currently a net exporter of wheat, barley, and potatoes. The EU is a net exporter of wine. On average, 56 Mt of wheat, 13 Mt of potatoe,s and 7.4 Mt of wine are exported by EU member states annually (2017 data; [14]. Steward Redqueen [37] estimated that a withdrawal of glyphosate would lead to trade balance worsening, and for some crops, this will become negative. Based on the analysis, almost 75% of the exportable excess of wheat and 80% of exportable excess of potatoes could be lost and wine exports could decline by 50%.

In the absence of glyphosate, these reductions in crop yield will result in additional land being required to maintain levels of production 3 [32, 40]. This will have significant environmental implications both in the EU as well as globally, as it means natural areas will be converted to agricultural use. For example, it was estimated that a 0.40 Mha increase in global cropland area, as a result of glyphosate withdrawal, would be associated with a 0.17 Mha global increase in deforestation and conversion of 0.24 Mha of pasture to cropland [4].

There are environmental implications associated with the use of glyphosate; its systemic nature enables it to control a broad range of plant species, including tenacious, deep-rooting perennials. Where poor application equipment and practices are used, non-target plants can be negatively impacted by the herbicide, reducing biodiversity at field edges. There is also the risk that due to the large volumes of this herbicide being used, it can travel in surface runoff and enter water bodies and be detected in concentrations above those set by the Drinking Water Directive [6, 35]. This risk is greatly reduced in conservation agriculture systems [35, 36].

There are numerous environmental benefits that arise from the use of glyphosate. The development of conservation tillage systems which leave the soil relatively undisturbed—with accumulation of organic matter protecting the soil surface and sequestering carbon [30]—has been enabled by the availability of glyphosate for weed management, as conservation agriculture is not compatible with more intensive cultivation approaches [27]. Conservation agriculture has been shown to benefit biodiversity of soil- and surface-dwelling organisms by maintaining continuous cover on the soil surface and by reducing or eliminating the disturbance of soil microbial communities through less or no-tillage, leaving them relatively intact and allowing them to thrive. The cover on the soil surface helps reduce the vulnerability of the soil to wind and rain erosion and therefore benefits both soil health and surface water quality. The use of glyphosate also facilitates a reduction in the depth and frequency of tillage practices (even on conventionally managed land) and therefore can reduce the fuel needed for crop establishment and subsequently contributes to lower greenhouse gas (GHG) emissions [23, 30].

At the EU-28 level, it is estimated that the withdrawal of glyphosate could result in 28 Mha of land (equal to half the surface area of France) that is currently managed under conservation tillage practices reverting to more conventional tillage practices (2010 data; [12]. This would be expected to increase fuel consumption there by 15–44 L ha^{-1}, resulting in an increase in GHG emissions of 1.4–3.8 Mt CO_2e per year [4, 23]. There would also be an increased loss of carbon from the soil as cultivation exposes conserved soil organic matter to oxidative processes and to increased erosion of the soil at or near the surface, which contains the highest levels of organic matter. This loss could equate to 80 Mt CO_2e, based on the whole of the conservation tillage area in the EU reverting back to conventional deep tillage practices to manage weeds. There is a great deal of uncertainty over the actual GHG emission impact, but what is clear is that withdrawing glyphosate would have a negative effect on the GHG emissions from agriculture at a time when significant efforts are being made to reduce all classes of GHG emissions [4].

There are also societal issues associated with a withdrawal of glyphosate. These include farmers having to change crop rotations to remain profitable and having less time to conduct other farming operations due to the increased labour requirements of alternative weed control methods [5, 22].

Ineffective control of weeds prior to crop establishment will increase the subsequent weed pressure and increase the weed seed bank in the soil. Additionally, with limited herbicides available that would only partially replace glyphosate, there would be an increasing need to use in-crop mechanical weeding to manage weeds that were not effectively controlled.

Conclusions

Glyphosate is the most frequently used herbicide within the EU for agricultural use. Its unique mode of action offers systemic control of a broad spectrum of weed species and is effective within a range of weed growth stages and timings. When it is used as part of an integrated weed management programme, it provides cost-effective weed management in a wide range of different crop species, ranging from widely grown commodity crops to smaller areas of more specialist crops.

The currently available chemical and non-chemical alternative approaches to weed management

- Are less flexible in timing of use;
- Require more time to conduct and need to be conducted during peak workload times;
- Are less effective at providing lasting control of such a broad range of species – weed control levels will decline and weed seed banks will increase;
- Are more costly;
- Can negatively impact soil structure and increase risk of erosion through wind and water processes;
- Often have higher GHG emissions through increased organic matter oxidation and fossil fuel use;
- Can reduce biodiversity in the soil and on the surface by affecting the production systems that can be used; and
- Are not all practical for use in conservation tillage systems.

The overall combination of lower yields and increased cost of production without commodity price increases is expected to reduce the viability of crop production in certain areas of Europe, especially where financial margins are already very tight. Where glyphosate remains available elsewhere in the world, a withdrawal in Europe would reduce the competitiveness of European commodity crops on the global market as the cost of production in other regions would be lower than in Europe. The reduction in production volumes in Europe would mean that there would be less surplus for export, negatively impacting the overall trade balance. Becoming a net importer of a particular agricultural commodity increases GHG emissions in two ways, through the increase in mechanical tillage required to partly replace the loss of the highly efficacious weed control provided by glyphosate and through the transportation of products from more distant regions that were once produced domestically or in nearby countries.

Without glyphosate the EU is calculated that there would be:

- Yield reductions of between 3 and 18% in wheat, 8 and 19% in barley, and 1 and 3% in Italian grape vines, rising to 12–20% in France (table and wine growing grapes);
- A decline in production of wheat by up to 24 Mt, potatoes by 10.4 Mt, and grape vines by 4.7 Mt;
- Increases in the cost of production by up to €10.5 billion in the EU wheat sector, just under €2 billion in the potato sector, and up to €4.2 billion in the grape vine sector;

- Negative environmental impacts from the increased tillage practices required to replace glyphosate through increasing soil erosion, threatening biodiversity within soils and increasing GHG emissions through higher fuel usage; and
- Increased fuel consumption per hectare by 15–44 L ha^{-1}, resulting in an increase in GHG emissions of 1.4–3.8 Mt CO_2e yr^{-1}.

Additionally, alternative weed control strategies can be logistically challenging to manage as increased labour is required at key times, often when the farm is busy with many other activities. With the COVID19 pandemic still ongoing, the shortage of agricultural labour availability in many countries is likely to continue.

There are potentially wider implications of a glyphosate withdrawal in Europe that were not specifically discussed in most of the studies analysed here. For example, the increased need for cultivation could result in release of soil stored carbon from all cropped European fields. Another example is that reduced production volumes may result in additional land being required either in Europe or elsewhere in the world to maintain production (exported to Europe), or to maintain self-sufficiency in food.

In total across wheat, potatoes, and vines, it is estimated that the loss of glyphosate could cost the industry (at the EU-28 level) over €16 billion in increased costs and lost production. The consensus for all assessed crops was that a loss of glyphosate would typically increase cost of production and reduce yields. If extrapolated to other crops grown in the EU that were not assessed, the total impact on European agriculture could be significantly higher. It is expected that in the absence of glyphosate, many of the current production systems, and some crop rotations would no longer be financially or practically viable. Significant investment would be needed to design and implement alternative production systems that provide reliable, consistent revenue and produce sufficient food to meet EU and global demands without significant negative impacts on the environment. This would require time to develop and is likely to lead to changes in the crops grown and the production locations. None of these holistic changes to the industry have been considered in any of the reviewed studies, and the full impact of glyphosate withdrawal in the medium to long term remains unknown but is certain to be very significant.

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Author contributions
SW was responsible for the conception, design, and editing of this work; EW was responsible for data analysis and interpretation, as well as revisions of the work. All the authors have read and approved the final manuscript.

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Availability of data and materials
Data are available by contacting lead author Sarah Wynn.

Declarations

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