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Glyphosate: environmental fate and impact

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Abstract

Glyphosate is the most used herbicide worldwide, which has contributed to concerns about its environmental impact. Compared with most other herbicides, glyphosate has a half-life in soil and water that is relatively short (averaging about 30 d in temperate climates), mostly due to microbial degradation. Its primary microbial product, aminomethylphosphonic acid, is slightly more persistent than glyphosate. In soil, glyphosate is virtually biologically inactive due to its strong binding to soil components. Glyphosate does not bioaccumulate in organisms, largely due to its high water solubility. Glyphosate-resistant crops have greatly facilitated reduced-tillage agriculture, thereby reducing soil loss, soil compaction, carbon dioxide emissions, and fossil fuel use. Agricultural economists have projected that loss of glyphosate would result in increased cropping area, some gained by deforestation, and an increase in environmental impact quotient of weed management. Some drift doses of glyphosate to non-target plants can cause increased plant growth (hormesis) and/or increased susceptibility to plant pathogens, although these non-target effects are not well documented. The preponderance of evidence confirms that glyphosate does not harm plants by interfering with mineral nutrition and that it has no agriculturally significant effects on soil microbiota. Glyphosate has a lower environmental impact quotient than most synthetic herbicide alternatives.

Introduction

Glyphosate is the most used (in terms of kilograms used per year) herbicide globally, mainly because of its heavy use in transgenic, glyphosate-resistant (GR) crops in the Western Hemisphere (Duke 2018a; Duke and Powles 2008). In the United States, more than 80% of the glyphosate used yearly in crops has been in GR crops for about 20 yr, but the total use plateaued at about 125 million kg year^{-1} in 2012 (USGS 2019). In 2014, 88% of the glyphosate used in U.S. agriculture was used in GR crops (Benbrook 2016). However, glyphosate is also widely used in places where GR crops are not grown, such as the European Union countries (e.g., Wiese et al. 2018) and for weed management in non-GR crops in the United States (Gaines 2018). It is not a low use-rate herbicide compared with most other herbicides introduced since the mid-1970s, when glyphosate entered the marketplace. Recommended use rates vary from about 0.84 to 1.7 kg ha^{-1}, depending on weed species, plant size, and other factors. Thus, enormous amounts of this relatively simple chemical enter the environment every year, and concern has grown over its potential environmental impacts.

Previous reviews have covered the environmental fate (e.g., Borggaard and Gimsing 2008) and, to a lesser degree, the environmental and ecological impacts of glyphosate (e.g., Cerdeira and Duke 2006; Giesy et al. 2000). An excellent, short, up-to-date discussion of this topic is the recent review by Blake and Pallett (2018). Thus, I will not repeat much of what is in these reviews in detail, but will instead try to distill the main findings of these publications and update what is known from more recent research results. The number of publications on glyphosate is enormous, and even those recent papers on topics that are germane to this paper are greater than can be cited in a mini-review. I have chosen representative papers that I think most clearly support the points that I make.

I will not discuss the animal toxicity of glyphosate in detail in this short review, other than to make a few observations. First, some of the toxicity studies are flawed, in that the studies do not differentiate between effects of formulation ingredients and glyphosate alone (e.g., Relyea and Jones 2009). Outside sprayed fields, organisms are much less likely to be exposed simultaneously to both glyphosate and its formulation ingredients. There is no question that the acute toxicity of glyphosate alone to mammals is very low (Williams et al. 2000). However, chronic toxicity of glyphosate has recently become a contentious issue. Recent extensive critical analyses of the toxicology literature and data have concluded that glyphosate is unlikely to pose a genotoxicity or carcinogenic risk to humans (Acquavella et al. 2016; Brusick et al. 2016; Kier and Kirkland 2013; Williams et al. 2016). Likewise, the U.S. EPA concluded the weight of evidence did not support any endocrine disruption effects of glyphosate (USEPA 2015) and that glyphosate is unlikely to be carcinogenic to humans (USEPA 2019). The European Food Safety Authority also found no evidence endocrine disruption by glyphosate (EFSA 2017), and it considers glyphosate unlikely to be carcinogenic (EFSA 2015). Finally, a panel of the U.S. National Academy of Sciences (Gould et al. 2016) concluded that "large numbers of experimental studies provided reasonable evidence that animals were not harmed by eating food from GE (genetically engineered) crops," that "livestock health before and after introduction of GE crops showed no adverse effects associated with GR crops," and that "epidemiological data on incidence of cancer and other human health problems over time found no substantial evidence that foods from GR crops were less safe" (p. xvii). This is germane, in that most GE crops are GR crops, and GR crops contain glyphosate residues that are generally below the levels permitted (e.g., Duke et al. 2003). Blake and Pallett (2018) review the acute toxicity of glyphosate to a range of aquatic and terrestrial organisms and conclude that, at exposures that are expected in nature, the likely effects are minimal to nil.

Glyphosate kills plants by inhibition of the shikimate pathway enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), an enzyme found only in plants and some microbes (Dill et al. 2010). Glyphosate is the only commercial herbicide with this site of action. There is no credible evidence of a secondary herbicide target of glyphosate, as plants with a GR form of EPSPS are about 50-fold resistant to glyphosate (Nandula et al. 2007).

Glyphosate's physicochemical properties are far outside those considered optimal for pesticides (Dayan 2018; Yu et al. 2018). In particular, glyphosate and its metabolites are very water soluble, which is one of the factors responsible for the lack of its bioaccumulation or biomagnification in organisms in nature. Another property of glyphosate is that it is an anion at physiological pHs and chelates or binds divalent metal cations well (Sundaram and Sundaram 1997). Glyphosate's phytotoxicity is eliminated or greatly diminished when bound to divalent metal cations (reviewed by Duke et al. 2012). Some have tried to implicate this chelating property with glyphosate's toxicity to plants and other organisms (Martinez et al. 2018; Mertins et al. 2018; Yamada et al. 2009), but chelation is easily shown not to contribute to glyphosate phytotoxicity. As mentioned earlier, plants that have been altered with only transgenes encoding a GR EPSPS from a microbe are 50-fold more resistant to glyphosate than unaltered plants (Nandula et al. 2007). A significant effect of glyphosate on any essential plant physiological process, such as mineral nutrition, would be evident at doses far below the doses that can adversely affect GR crops. Furthermore, in well-replicated studies in space and time, the mineral composition of GR crops is not altered by application of recommended doses of glyphosate for weed management (Costa et al. 2018; Duke et al. 2012, 2018b; Kandel et al. 2015; Reddy et al. 2018). This literature is summarized by Duke and Reddy (2018). They provide U.S. yield data of maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] from 1980 through 2017. The increases in yield during this time have been close to linear, with no inflection of the yield curves after 1996, after which 90% or more of these three crops became GR varieties in the United States. The steady increase in yield of these three crops in the United States after adoption of GR technology is inconsistent with glyphosate having any adverse effect on the physiology of plants other than those resulting from inhibition of EPSPS. This lack of an effect on plants other than via inhibition of EPSPS reduces the probability of glyphosate affecting potential molecular targets that are similar for plants and animals and other off-target organisms at the concentrations of glyphosate to which organisms outside fields are likely to be exposed.

Glyphosate's Fate in Soil, Water, and Plants

Nonbiological Processes

A large proportion of the glyphosate entering the environment does so in sprayed fields. The larger the field, the higher the proportion of applied glyphosate that arrives on the sprayed field because of the larger area to perimeter ratio. A very high proportion of glyphosate is used with agronomic crops, particularly GR crops, that are mostly grown on larger fields than nonagronomic crops. The vapor pressures of the glyphosate acid and the isopropylamine salt of glyphosate are 0.0131 and 0.0021 mPa (National Pesticide Information Center n.d.), making it virtually nonvolatile. Therefore, glyphosate arrives on vegetation or soil surfaces almost entirely in spray droplets. The glyphosate that adheres to vegetation surfaces from spray droplets is either taken up by the plant or washed off the plant to the soil by precipitation. Glyphosate taken up by plants is either exuded from roots (Coupland and Caseley 1979; Laitenen et al. 2007) or leached from plant residues. Little is known of these latter two processes under field conditions. However, Mamy et al. (2016) found that glyphosate taken up by GR and non-GR canola (*Brassica napus* L.) was lost very slowly from plant residues in the field, increasing the persistence of glyphosate in sprayed fields. This effect was more pronounced in GR canola than non-GR canola, because the GR plants took up more glyphosate.

Once in the soil, glyphosate is bound tightly by mostly nonorganic soil components, particularly charged minerals such as aluminum and iron oxides (Borggaard and Gimsing 2008). It is more tightly bound to soils than most other herbicides and competes for adsorption sites in soil with phosphate, so phosphate fertilizers can cause remobilization of glyphosate (Bott et al. 2011). In extreme cases, this phenomenon can result in phytotoxicity to plants from unbound glyphosate. Also, in very sandy soils without enough binding sites, glyphosate residues can cause phytotoxicity (e.g., Cornish 1992).

In most soils, the majority of glyphosate and its main metabolite, aminomethylphosphonic acid (AMPA), are found in the top 1 cm of soil (e.g., Okada et al. 2016). Glyphosate does not move readily from most soils to either ground- or surface water (Borggaard and Gimsing 2008). Leaching is greater in soils containing sand and/or gravel and those with macropores. AMPA is slightly more mobile than glyphosate in soil (Kjaer et al. 2005), which contributes to it greater likelihood of being found in both ground- and surface water. Typically, less than 1% of the glyphosate applied to fields is lost as runoff to surface water. Edwards et al. (1980) found >99% of the small percentage (1.85%) of glyphosate that moved to runoff in fields sprayed with twice the recommended rate occurred during a heavy rainfall event the day after application. Glyphosate in surface water eventually adsorbs to sediments, where it undergoes similar biological degradation processes as in soils (Wang et al. 2016).

Biological Processes

Glyphosate degradation in soil is almost entirely due to microbial degradation, as it degrades much faster in nonsterile than sterile soils (reviewed by Borggaard and Gimsing 2008). There are two enzymatic routes of glyphosate degradation. The predominant degradation route is by glyphosate oxidoreductase (GOX), which produces AMPA and glyoxylate. Glyoxylate is a common natural metabolic compound, whereas the AMPA found in the environment comes from glyphosate degradation and degradation of

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phosphorous-containing detergents (Botta et al. 2009). The other route of degradation is through a carbon-phosphorous (C-P) lyase that produces the natural product sarcosine (*N*-methyl glycine) and inorganic phosphate. More rapid degradation of sarcosine than AMPA in soil might skew our perceptions about the relative importance of these degradation processes. The rate of glyphosate degradation in soil varies between soils and within the same soil, depending on many factors. For example, the degradation rate is faster in aerobic than anaerobic soils. Half-life values of 1.0 to 67.7 d have been reported for glyphosate in soils (EFSA 2015). In a broad range of agricultural soils with different properties, Nguyen et al. (2018) found glyphosate degradation during 32 d ranged from 7% to 70%. Degradation strongly correlated with the soil exchangeable acidity (H^+ and Al^{3+}), exchangeable Ca^{3+} ions, and ammonium lactate-extractable potassium. Blake and Pallett (2018) state that the average half-life of glyphosate in soil is about 30 d, with a range of 5.7 to 40.9 d.

A small body of literature discusses bioremediation of soils with high glyphosate content (e.g., Zhan et al. 2018). However, there are no studies that confirm that glyphosate substantially builds up in soils, even after long-term use of glyphosate in GR crops. Glyphosate is used extensively in Europe in non-GR croplands (e.g., Wiese et al. 2018). In a survey of 317 different European topsoils where GR crops were not grown, glyphosate and AMPA were found in 21% and 42% of the soils, respectively (Silva et al. 2018). AMPA contamination was almost always higher than that of glyphosate, and most levels were less than 0.5 mg kg^{-1} of soil. Unfortunately, I found no studies of glyphosate and AMPA levels in soils with documentation of yearly long-term use of glyphosate with GR crops. The lack of crop yield reduction in soils with long-term glyphosate use (Duke et al. 2018b; Reddy et al. 2018) indicates that if glyphosate has accumulated in such soils, it is not bioavailable as a herbicide.

Another unanswered question is whether long-term use of glyphosate leads to its accelerated degradation, a phenomenon that is common for other herbicides (e.g., Yale et al. 2017). Early work provided evidence that accelerated degradation of glyphosate can occur with repeated use (Robertson and Alexander 1994), but I found no subsequent studies of this phenomenon in field situations with long-term use of glyphosate. Because some microbes can use glyphosate as a sole source of phosphorous (reviewed by Zhan et al. 2018), one might expect that such microbes would become more abundant in soil where glyphosate is consistently used annually. Glyphosate application to soils can increase the degradation rate of other herbicides (e.g., Bonfleur et al. 2011; Lancaster et al. 2008). Considering the relatively short half-life of glyphosate in soils, the most probable use of bioremediation of glyphosate in soils would be after accidental spills of significant magnitude.

AMPA degradation requires a C-P lyase enzyme, and AMPA is more environmentally persistent than glyphosate. In at least one microbe, the C-P lyase that metabolizes glyphosate is even more active on AMPA (Selvapanidiyan and Bhatnagar 1994). If this is the case for other microbes with C-P lyase, the greater persistence of AMPA than glyphosate in soils may indicate that microbes that use this degradation pathway are less common than those with GOX. Microbes with such a C-P lyase can use either glyphosate or AMPA as a sole source of phosphorous (Selvapanidiyan and Bhatnagar 1994). The biochemistry and genetics of C-P lyases that metabolize glyphosate and AMPA is reviewed by Hove-Jensen et al. (2014).

Glyphosate is also metabolized by plants (reviewed by Duke 2011). Both GOX-mediated and C-P lyase–mediated biological processes can occur in plants, but metabolic degradation of glyphosate by GOX is predominant. The production of AMPA from glyphosate varies considerably between species. No clear generalization can be made, but legumes seem to metabolize glyphosate more than grasses (Reddy et al. 2008). A large proportion of the glyphosate taken up by GR soybeans and canola at standard application rates is degraded to AMPA (Duke et al. 2003; Corrêa et al. 2016). These plants are completely resistant to glyphosate at such application rates (Nandula et al. 2007), and therefore the mechanism for degradation is unaffected by secondary effects of glyphosate phytotoxicity. The first commercial versions of GR canola contained transgenes for both a microbial GR EPSPS and a microbial GOX with high activity. GR maize metabolizes much less of the glyphosate that it takes up than canola or soybean (Costa et al. 2018; Duke et al. 2018b).

All current GR crops are made resistant only with transgenes encoding a GR EPSPS, so the degradation of glyphosate in these crops is entirely due to enzymes of the crop or its endophytes (Nandula et al. 2019). At this time, none of the many weed species that are documented to have evolved resistance to glyphosate (Heap and Duke 2018) have been rigorously shown to have done so by increasing their capacity to metabolically degrade the herbicide. However, because most species appear to have gene-encoded enzymes for glyphosate metabolism, I expect that we will eventually find we are selecting for weeds with greater capacity for metabolizing glyphosate. This may incrementally reduce the half-life of glyphosate in the environment.

The amount of glyphosate that is degraded to AMPA in most glyphosate-susceptible plants is probably small, as a significant dose of glyphosate will probably compromise metabolic activity or kill the plant before much of the glyphosate can be degraded. This would be the case in non-GR crops, where the herbicide is most often sprayed before planting or after harvest. Furthermore, in these situations, much of the glyphosate sprayed does not come in contact with living plants, but enters the soil rather quickly, where it is immobilized and then metabolized. The main exception in non-GR crops is when glyphosate is used to kill the crop so that it will desiccate in order to facilitate harvesting. This practice is common with densely planted crops such as wheat (*Triticum aestivum* L.) that are likely to almost completely intercept the glyphosate spray. In the case of wheat, most of the glyphosate taken up is found in the straw, with much less in the seed, and relatively little AMPA is found (Cessna et al. 1994). In a crop like this, in which glyphosate is used as a harvest aid, most of the glyphosate reaching the soil or surface water arrives via wash-off from the crop or leaching from crop residues.

Real and Potential Effects on Non-target Vegetation and Microbes

Although some have discussed the potential effects of glyphosate on non-target vegetation by root exposure (Saunders and Pezeshki 2015), this type of exposure is almost irrelevant, as glyphosate is almost entirely inactive as a herbicide in soil. If there were a problem, farmers would not plant crops into soil on which glyphosate was used just days earlier to kill weeds before planting. Also, even if glyphosate were bioavailable in soil, glyphosate is not very effectively taken up and translocated basipetally by roots, and the concentrations reported in surface-water runoff are generally lower than the doses needed for a significant phytotoxic effect.

Glyphosate drifting from sprayed fields is the main source of exposure of non-target plants. The dose of glyphosate needed to

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cause phytotoxicity varies between species, and drift levels of glyphosate also vary considerably. Because glyphosate translocates readily from foliage to growing parts of the plant, good coverage of the target weed is not needed for efficacy. Thus, large spray droplets, without good coverage of the weed, are effective in delivering lethal glyphosate doses to target plants. In most cases, the larger the spray droplet, the smaller the drift problem, especially for an essentially nonvolatile compound like glyphosate. Even with aerial spraying of glyphosate, plant injury is usually minimal at distances of >20 m downwind from sprayed fields (Marrs et al. 1993; Reddy et al. 2010). For mature plants of many species, there is minimal damage at distances of less than 20 m. Wild plant species are generally less sensitive to glyphosate than domesticated plant species (Cederland 2017). An analysis by Cederland (2017) found that drift of 5 g ae h^{-1} of glyphosate would result in minor adverse effects of drift on 95% of plant species and that drift levels of 1 to 2 g ae h^{-1} of glyphosate would essentially cause no harm to vascular plants. However, there can be growth stimulation effects of glyphosate at low doses.

Hormesis is the stimulatory effect of a subtoxic dose of a toxin. Hormesis is common with herbicides and occurs at doses just below the dose of the threshold for phytotoxicty (Belz and Duke 2014). Subtoxic doses of glyphosate can cause the most profound cases of hormesis seen among herbicides, especially in woody plants (Brito et al. 2018). Growth stimulation by glyphosate can reach 70% with some species, but is generally between 20% and 30%, especially in herbaceous species. Phytotoxic effects of glyphosate drift on plants near agricultural fields are well documented, but hormesis caused by drift of glyphosate in the field has not been studied. Whether hormesis benefits, harms, or is neutral to the fitness of a plant species in a natural habitat has not been determined, but it would probably depend on what developmental parameter is affected and how much and when it is affected. Subtoxic doses of glyphosate can change the size distribution of plants of the same species in a population (Belz et al. 2018), which could affect the performance and development of that population. The low doses of glyphosate arriving in streams or other bodies of water via runoff or drift could stimulate the growth of some algae via hormesis (e.g., Dabney and Patiño 2018). This effect could be problematic or not, depending on the algal species affected and the magnitude of the effect. But enhanced growth of algae as a result of glyphosate hormesis is only 20% or less (Cedergreen et al. 2007; Dabney and Patiño 2018), a magnitude of effect that is unlikely to cause serious problems.

Another potential effect of glyphosate on non-target vegetation is indirect. Inhibition of EPSPS reduces production of shikimic acid pathway–derived compounds, such as some phytoalexins and lignans, that plants use to protect themselves from microbial plant pathogens (Hammerschmidt 2018). This effect is so pronounced that the amount of glyphosate needed to kill a weed is significantly less when plant pathogens are present (reviewed by Duke 2018b). However, glyphosate is toxic to some microbes, particularly rusts (e.g., Feng et al. 2005), so the interaction of drift levels of glyphosate with plant pathogens will depend on the organism and the dose. For example, some drift levels of glyphosate can reduce severity of rust infection of grand eucalyptus (*Eucalyptus grandis* W. Hill ex Maid.) leaves (dos Santos et al. 2019). Almost nothing is known of the effects of glyphosate on plant disease outside sprayed fields, but doses that are phytotoxic should weaken defenses of non-GR plants to many microbial plant pathogens. Such an effect could increase the level of plant pathogen propagules in the vicinity of such affected plants (Hammerschmidt 2018).

As with any sprayed herbicide, movement of the herbicide from the intended site of application can affect off-site vegetation. The effects vary with drift dose, plant species, environmental conditions, and other factors. Because glyphosate is a nonselective herbicide, more plant species might be expected to be affected than by drift of selective herbicides. However, in most cases, glyphosate replaced several selective herbicides, so in these cases, the effects of glyphosate on non-target vegetation should be contrasted with the combined effects of the herbicides that it replaced. In comparison with many of the herbicides that it replaced, glyphosate has a relatively short environmental half-life and lower drift potential, which could mean that adverse effects on non-target vegetation are likely to be less, or at the most similar. With the increasing evolution and spread of glyphosate resistance (Heap and Duke 2018), some of the herbicides that glyphosate replaced are now being sprayed in addition to glyphosate.

As mentioned earlier, some microbes can use glyphosate as a phosphorus source. But some microbes have glyphosate-sensitive EPSPS (Dill et al. 2010). So glyphosate might be expected to disrupt soil microflora, providing a benefit to some and being toxic to others. However, we do not know how bioavailable glyphosate is to specific microbes in soil, where it is tightly bound. Studies of glyphosate effects on soil microflora, using glyphosate levels that could be found in agricultural soil, have generally found minor effects that do not last long (e.g., Nguyen et al. 2016). In one case, even when applied at 3X the recommended field rates, glyphosate had only small and transient effects on soil microbial communities (Weaver et al. 2007). The fact that yields of GR crops continue to increase (Duke and Reddy 2018) supports the view that any effects of glyphosate on soil microbes of croplands are minor. The much lower levels of glyphosate that might be found in off-site soils are likely to have undetectable or no effects on soil microflora.

Phytotoxicity of glyphosate to non-target plant species outside fields can influence ecosystems, especially if it changes the species composition of an ecosystem. For example, glyphosate could have an adverse effect on an animal species that depends on a plant species that is substantially adversely impacted by glyphosate, especially if both species are native to a region in which glyphosate is heavily used. Both the monarch butterfly (*Danaus plexippus* L.) and certain *Asclepias* species upon which the butterfly exclusively depends are found in the parts of North America where glyphosate is heavily used because of the adoption of GR soybean and maize. Thus, some have attributed the decline of this butterfly to glyphosate use (e.g., Pleasants and Oberhauser 2013). However, a recent analysis by Boyle et al. (2019) report that the decline of *D. plexippus* predates the adoption of GR crops. Their analysis shows that the decline of both the *Asclepias* spp. and *D. plexippus* in North America began at close to the same time, when there was a widespread shift to synthetic herbicide–based weed management in the late 1940s and early 1950s. Synthetic insecticide use also increased dramatically at this time. There is no inflection of the decline plot of either the plant or butterfly with the widespread adoption of GR crops (Boyle et al. 2019). Hartzler (2010) found little effect of adoption of GR crops in Iowa on common milkweed (*Asclepias syriaca* L.), the main milkweed species host of *D. plexippus*, outside agricultural fields, where insecticides are not used. However, in agricultural fields, where insecticides are often sprayed, there was a reduction in this host plant after the introduction of GR crops. Host plants in fields where insecticides are used could be considered an attract-and-kill situation for *D. plexippus*. Thus, as long as insecticides are sprayed in crops, *Asclepias* spp. growing in such crops could be more of a risk than a benefit to *D. plexippus*.

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Therefore, glyphosate reducing *A. syriaca* in GR crops, while having almost no effect on this plant species outside fields where insecticides are not sprayed, could benefit the butterfly. This is a complex example that illustrates that conclusions based on incomplete knowledge of all factors affecting a species or ecosystem can be misleading.

Effects of Glyphosate/GR Crop Technology

Tillage is practiced primarily to manage weeds. Other than taking land out of nature, the most substantial and long-term environmental damage caused by growing crops is soil erosion due to tillage. Topsoil can take centuries or more to replace, whereas persistence of glyphosate residues is short-lived. In some cases, damage by tillage is essentially irreversible. Additionally, soil movement to streams and other bodies of water disrupts ecosystems. Tillage also contributes to soil compaction (e.g., Yadav et al. 2016). Before the introduction of GR crops, glyphosate use after planting was limited by the sensitivity of all crops to this nonselective herbicide.

Because all weeds were susceptible to glyphosate, which can only be used as a foliar application, the use of glyphosate in GR crops could be done without tillage to adequately control weeds in most situations. The reduction in tillage enabled by GR crops led to less soil erosion and water contamination (reviewed by Cerdeira and Duke 2006, 2010; Duke and Powles 2009). The full reduction of environmental harm from reduced-tillage (RT) and no-tillage (NT) agriculture due to adoption of GR/glyphosate technology has not been well studied, but the high levels of adoption of RT and NT farming due to GR crop use, before the widespread evolution of GR weeds, was well documented (e.g., Givens et al. 2009; Trigo and Cap 2003).

Agriculture is a major contributor to greenhouse gas emissions (Lamb et al. 2016). It does so by taking land from its natural state, in which more carbon is sequestered, and by the use of fossil fuels for modern farming equipment. For example, in soybeans in rotation with maize, 45, 115, and 145 kg C ha^{-1} yr^{-1} are released in NT, RT, and conventional tillage systems, respectively (Barfoot and Brookes 2014). Thus, the NT system provides a net sink of 100 kg C ha^{-1} yr^{-1}. Tillage is a major part of the contribution of modern farm equipment to CO_2 production. Adoption of NT and RT production reduced CO_2 emissions from plowing by 72 and 27 kg ha^{-1}, respectively, in soybeans and 65 and 20 kg ha^{-1}, respectively, in maize (Barfoot and Brookes 2014). In 2016, use of GR crops reduced worldwide fossil fuel use in agriculture the equivalent of removing 1.8 million family cars from the road for 1 yr (Brookes and Barfoot 2018).

Estimates of the effect of GR technology on relative environmental effects, comparing the acute mammalian toxicity of glyphosate to the herbicide regime that it replaced, have been favorable for GR crops (Gardner and Nelson 2008; Nelson and Bullock 2003). Gardner and Nelson (2008) calculated that the number of mammalian LC_{50} doses of herbicide used per hectare were reduced by 100 and 500 in soybeans and cotton, respectively, by adoption of GR crops. Barfoot and Brookes (2014) found that the adoption of GR soybeans, maize, and cotton reduced the environmental impact quotient (EIQ) of these crops by 15%, 13%, and 9%, respectively, averaged worldwide. Two years later, these EIQ reduction values for GR soybean, maize, cotton, canola, and sugar beet (*Beta vulgaris* L.) were 13%, 13%, 11%, 30%, and 19% (Brookes and Barfoot 2018). Kniss (2017) found that herbicide applications have gone up for the past 25 yr in maize, cotton, and soybeans in the United States, but herbicide acute hazard quotients were reduced after adoption of GR crops. Herbicide chronic hazard quotients were also reduced in soybean, but increased in cotton, and remained the same in maize. However, glyphosate accounted for only 0.1%, 0.3%, and 3.5% of the herbicide chronic toxicity quotients in maize, soybean, and cotton, respectively. A major point was that glyphosate plays only a small role in contributing to the toxicity hazard of herbicide use. Loss of glyphosate as a herbicide option in seven countries (Australia, China, India, Indonesia, Philippines, Thailand, and Vietnam) is estimated to increase the EIQ of herbicide use by 0.4% to 11.6%, depending on the country (Brookes 2019).

Sustainable, intensive agriculture is the only clear future alternative to removing more land from its natural state for crops in order to fulfill humanity's growing food needs (Balmford et al. 2018). The loss of glyphosate would require a worldwide increase of 762,000 ha in cropland to maintain current crop production, 53% of which would have to be derived from new land brought into cropping production, including 167,000 ha of deforestation (Brookes et al. 2017). For the major field crops that feed the world, wise use of herbicides will continue to be part of crop production technology for the foreseeable future. Loss of the once in a century herbicide glyphosate (Duke and Powles 2008; Duke et al. 2018a) as part of this future would be costly for both farmers and the public.

Evolution of GR weeds (Heap and Duke 2018) jeopardizes the environmental benefits that were obtained by using glyphosate alone in GR crops. Because of the increase in GR weeds and weeds resistant to other herbicide classes, tillage has become a more viable option. Other herbicides are now used more often with glyphosate in GR crops. Thus, evolutionary responses to the almost ideal glyphosate/GR crop technology for weed management are eroding its environmental benefits.

Conclusions

The preponderance of evidence indicates that the net influence of glyphosate on the environment has been generally positive when comparing its use with the weed management methods that it replaced. Glyphosate binds tightly to most soils, reducing its movement to ground- and surface water. It has a relatively short environmental half-life, being metabolized rapidly by many soil microbes. Adoption of GR crops reduced tillage practices, increasing soil retention of carbon and decreasing use of fossil fuel in agriculture. The EIQ of weed management was reduced by the adoption of GR crops. However, evolution for GR weeds is eroding the environmental benefits of glyphosate/GR crop technology.

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