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# The Future of Glyphosate in Australian Agriculture?

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## Abstract

Glyphosate is a herbicide used widely in Australian and global agriculture. We examine policy, legal and environmental influences over its use. The likely economic consequences for farm businesses and food consumers of widespread bans on the use of glyphosate in agriculture are discussed. We outline why Australian agriculture and Australian food consumers, compared to those in other key global regions, would be comparatively less affected by an unlikely global ban on glyphosate. From an Australian public policy perspective, we argue that chemical registration of herbicides should continue to be evidence-based. However, we also recommend greater investment by government to better understand societal concerns regarding herbicides. Enhanced social engagement and two-way communication will help secure and build trust in an evidence-based policy response to chemical use in Australia.

***Keywords***: glyphosate, farming, grain production, grain prices

## Introduction

Glyphosate is a non-selective herbicide first commercialised by Monsanto in 1974. It prevents plants from making proteins required for plant growth (Duke and Powles, 2008). Internationally, as glyphosate's efficacy as a weedicide became widely known, and its real cost lowered, and especially when major crops were bred to tolerate applications of glyphosate, use of glyphosate became widespread. It is now the most widely used herbicide in agriculture across the globe, with total use each year estimated at 700,000 tonnes (Maggi *et al.,* 2019).

Glyphosate's efficacy as a non-selective herbicide altered crop management and crop selection, especially when glyphosate tolerant (GT) crops became available in several key grain-producing regions of the world (Brookes and Barfoot, 2014). GT crops such as RoundUp Ready® maize and RoundUp Ready® soybean are now grown on over 191.1 million hectares globally with the United States, Brazil, Argentina, Canada, and India collectively supplying 91 per cent of the global biotech crop area (ISAAA, 2019). Application of glyphosate on GT crops accounts for 56 per cent of global glyphosate use (Benbrook, 2016).

Australian farmers, like many farmers in other countries, now frequently use glyphosate. It first became available in Australia in 1974. From 1997 to 2003, glyphosate use increased almost fourfold in Australia (DAWE, 2007). In evidence to the Australian Government Rural and Regional Affairs and Transport Committee (2019), Bayer Crop Science stated that: "around $400 million of glyphosate based products are sold in the Australian market each year—the largest selling agricultural chemical product on the Australian market." (p. 58). Harries *et al.* (2020) report on Western Australian farmers' use of glyphosate. These farmers produce around 40 per cent of Australia's grain. These farmers apply glyphosate about once per year per field, at a rate of 500-750 grams of active ingredient per hectare.

## Environmental and Legal Influences on Glyphosate Use in Australian Agriculture

### Glyphosate tolerant crops

The breeding of GT crops in Australia, and more importantly globally, allowed glyphosate to be used regularly as a broad-spectrum selective post-emergent herbicide. There are two GT crops grown in Australia: cotton and canola (OGTR, 2020). Nearly all cotton grown in Australia is GT cotton (Werth *et al*., 2011) and GT canola was introduced in the late 2000s. By 2017, 21 per cent of the national canola crop was GT canola (OGTR, 2020). Most GT canola grown in Australia is glyphosate-tolerant canola, although the Office of the Gene Technology Regulator has approved the commercial scale testing of glufosinate-tolerant and glyphosate-tolerant canola (OGTR, 2021).

Initial public opposition to introducing GT crops to Australia fuelled policy conservatism and even opposition to GT crops in many Australian States. Most state governments invoked moratoriums on the introduction of GT crops. However, by July 2021 the only remaining moratorium is in Tasmania where its government extended its ban on genetically modified (GM) crops until 2029; and in South Australia, where the ban only now applies to Kangaroo Island.

To regulate the introduction of GT crops, and GM technology in general, Australia's national government introduced the Office of the Gene Technology Regulator (OGTR), established under the Commonwealth Gene Technology Act 2000. The Office continues to oversee the regulation of gene technology in Australia and is obliged to protect the health and safety of people, and the environment, through regulating and licensing activities associated with GM organisms (including GM crops such as GT crops). The Australian Pesticides and Veterinary Medicine Authority (APVMA) and Food Standards Australia New Zealand (FSANZ) also have a national role in approving the commercial use of glyphosate with any GM herbicide tolerance technology and each Australian state regulates use of this technology in their state.

Due to public oppositional campaigns to GM crops, Australia has had a short history of GT crop production compared to the United States, Argentina, Brazil and Canada who were quick to adopt these crops after their commercialisation in the 1990s (Heap and Duke, 2018). Australia is an anomaly among these countries, as GT crops make up only a small proportion of Australia's crop area. The main grains grown in Australia, by far, are wheat and barley which are not GT crops, although there are varieties of other crop species approved to be grown that have a tolerance to other chemicals (e.g. triazine-tolerant canola).

GT maize and GT soybeans are not grown in Australia, not only due to public opposition to these crops but also due to a paucity of large areas within Australia with reliable climates that suit these high-yielding summer crops (GAEZ-FAO, 2012; Ray *et al.,* 2013). Australia's domestic markets also lack demand for these grains. Australia's major livestock industries, beef and sheep production, mostly are based on extensive grazing of pastures and rangelands (Hegarty *et al.,* 2010; Henry *et al.,* 2012), although supplementary grain feeding, especially during dry periods is increasingly commonplace. Australia also lacks a large internal bioenergy market that could be served by GT feed grains like GT maize. By contrast, in the United States 45 per cent of maize produced is used to produce ethanol for biofuel (Hoekman *et al.,* 2018). Unlike the United States or Brazil, Australia has no domestic policy that strongly encourages use of biofuels (Chum *et al.,* 2014). Hence, apart from GT canola and GT cotton, most crops grown in Australia are not *specifically* dependent on repeated applications of glyphosate and therefore crop production systems are less vulnerable to a ban on the use of glyphosate compared to many crop production systems in North and South America that feature GT crops.

**Environmental influences on glyphosate use: climate change**

Changes in crop establishment techniques in Australia have occurred in part as a response to a long-term decline in growing season rainfall (Turner, 2011; CSIRO & BOM, 2018). The reduced availability of dryland agriculture's most important input, water, has made improving water use efficiency a priority in farm management. Changes in agronomic practices, such as no tillage and reducing weeds through applications of the herbicide glyphosate, have improved water use efficiency (Turner, 2011). The expiration of glyphosate's patent, and its subsequent price drop, also have aided adoption of no-tillage practices and their accompanied use of glyphosate (D'Emden *et al.,* 2006).

Along with water limitations, labour scarcity also has emerged to restrict agricultural production (Rabobank, 2007). In response, farm owners have opted to work more hours themselves and have shifted away from labour-intensive enterprises such as intensive sheep production. Most large-scale farmers in the 1990s and 2000s altered their enterprise mix to favour cropping (Doole *et al.,* 2009). Glyphosate simplified weed control in cropping systems and reduced the labour required to manage weeds via repeated tillage.

To adapt to declining in-season rainfall and to accommodate larger cropping programs, Australian crop farmers also have moved to dry seeding, as the resulting crops use water more efficiently (Kirkegaard and Hunt, 2010). But this has limited the use of glyphosate. Dry seeding is where the seed is sown into dry soil before the opening rains that trigger the growing season (Fletcher *et al*., 2020). Dry seeding allows seeding to take place over a longer period, thereby reducing capital expenditure on high work rate and large seeding machinery. Labour constraints over the seeding period are also lessened by dry seeding (Fletcher *et al.,* 2016). However, a non-selective preemergent herbicide such as glyphosate cannot be used to kill weeds when dry seeding. This is especially an issue if weed density in a paddock is high. The use of glyphosate requires a delay to seeding, which incurs yield penalties (Beckie *et al*., 2020) relative to dry sowing. The later sowing with glyphosate occurs when soils are wetter and cooler, causing slower seedling emergence and plant growth; and the subsequent use of in-season rainfall is less effective (Fletcher *et al*., 2020). Delayed seeding also reduces the competitiveness of a crop, potentially resulting in weed species like annual ryegrass (*Lolium rigidum*) having greater seed production, increasing the future challenge from weeds (Gill and Fleet, 2020). In short, dry seeding and its yield benefits encourage a move away from non-selective preemergent herbicides, such as glyphosate, towards other weed control methods compatible with dry seeding (Beckie *et al*., 2020). However, it should be noted that effective dry seeding is reliant on effective weed control, including over summer or in early break years. In those situations, access to glyphosate as a non-selective herbicide is very valuable and is essential if the effectiveness of dry seeding is to be maintained.

**Environmental influences on glyphosate use: herbicide tolerant weeds**

Weeds lessen crop yields and reduce agricultural productivity (Oerke, 2006). Weed management in Australian agriculture has been estimated to cost $2.5 billion annually and yield losses associated with weeds to cost $745 million annually (Llewellyn *et al.,* 2016). Sinden *et al*. (2004) reported even higher cost estimates. Weed management in Australia has greatly depended on access to glyphosate as a non-selective weed killer over the last three decades. However, the ubiquitous use of glyphosate has become tempered by the emergence of weed populations resistant to glyphosate that lessen glyphosate's efficacy as a weedicide and limit its widespread use (Green, 2018). Initially, due to glyphosate's effectiveness in controlling weeds, the methods of weed control in Australian cropping systems became less diverse. The sole or main reliance on glyphosate, combined with its repetitious use, increased the selection pressure for weeds with biological characteristics that tolerated glyphosate applications (Werth *et al.,* 2013).

In 1996 the first glyphosate resistant weed, annual ryegrass (*Lolium rigidum*), was documented in Australia (Powles *et al.,* 1998). Currently in Australia there are 17 species of glyphosate resistant weeds. To control these weeds, farmers now apply selective herbicides in conjunction with glyphosate (Beckie *et al*., 2020). The continued emergence of weed populations displaying resistance to glyphosate limits the greater use of glyphosate in Australia's cropping systems.

One positive from this restriction on the use of glyphosate is a heightened interest in integrated weed management which involves farmers using several weed control methods (Pannell and Gill, 1994; Pannell *et al*., 2004), thereby restricting the occurrence of glyphosate resistant weed populations. Integrated weed management is now widely applied throughout Australia. A survey of Western Australian farmers by Llewellyn *et al.* (2004) found the mean number of different weed control practices used was 7.7. Integrated weed management includes non-herbicide weed control methods such as harvest weed seed control (Jacobs and Kingwell, 2016) and tillage based site-specific weed control and rotations to manage weeds (Pannell *et al*., 2004). Harvest weed seed control systems are effective at high weed densities (Walsh *et al.,* 2013), whereas site-specific weed control is especially valuable at low densities, as it removes the need for whole-field treatments (Walsh *et al.*, 2020). These technologies provide effective non-chemical alternatives and allow for dry seeding (Walsh *et al.,* 2013). However, loss of access to herbicides, like glyphosate, increase integrated weed management control costs and complicate farmers' weed management decisions.

**International legal influences on glyphosate use**

Since 2015 a number of epidemiological studies (Myers *et al.,* 2016; Zhanga *et al.,* 2019; Leon *et al.,* 2019) have led to the questioning of how benign to health is repeated exposure to glyphosate; and in turn successful law suits have been spawned. A key report on the health risk of glyphosate from the International Agency for Research on Cancer (IARC, 2015), part of the World Health Organisation (WHO), classified glyphosate as a Group 2A product, "probably carcinogenic to humans". That report triggered public concern about the safety of glyphosate, despite the United States Environmental Protection Agency deeming the herbicide safe to use when used in accordance with instructions (USEPA, 2016). In Australia, the APVMA (2017) also assessed glyphosate as safe when used in accordance with instructions. Kniss (2017) examined the long-term trends in the intensity and relative toxicity of herbicide use in the United States and found glyphosate less acutely toxic than 94 per cent of the 159 herbicides in use over the 25-year survey period. Also, the way the original IARC (2015) report was constructed, and non-transparently edited, to impugn the safety of glyphosate has attracted adverse media attention (Kabat, 2017; Kelland, 2017). Nonetheless, legal cases have been brought against Monsanto, now owned by Bayer, for damages relating to glyphosate causing cancer.

In the United States over 125,000 lawsuits against Bayer were lodged by those claiming glyphosate to be the cause of their cancers (Hals, 2021). In 2019 Australia's first case was brought against Monsanto claiming glyphosate use played a part in the claimant developing non-Hodgkin's lymphoma. There is currently a class action lawsuit before the federal courts against Bayer in Australia for misleading its customers, by suggesting glyphosate posed no health risks when used in accordance with label instructions.

In the United States in June 2020, Bayer announced it would spend up to $US10.9 billion to settle approximately 95,000 lawsuits brought by individuals who claimed their non-Hodgkin's lymphoma was due to their exposure to glyphosate (ABC, 2020). Up to $US5 billion was paid out in 2020, and another $US5.1 billion is to be paid in 2021. In June 2020, Bayer also filed a class action in San Francisco to settle all future claims of individuals who use Roundup (i.e. glyphosate) but have not yet manifested non-Hodgkin's lymphoma. Bayer also announced the creation of a special science panel which, over the following four years, would study Roundup and render a decision on whether the herbicide caused non-Hodgkin's lymphoma.

Against the backdrop of this litigation and emerging potentially adverse health findings concerning the use of glyphosate, a proscribed social licence governing use of glyphosate is arising. The combined influences of successful legal cases and the accompanying furore of adverse social media attention are pressuring various governments to act. Glyphosate use in public spaces has now been banned in countries such as the Netherlands, France and Italy (Tosun *et al.,* 2019; Malkanthi *et al.,* 2019). The six Middle East gulf countries have issued glyphosate bans from 2019, as has Vietnam. In 2019, Thailand announced its intention to prohibit the production, importation, exportation and possession of glyphosate, paraquat and chlorpyrifos by June 2020. However, soon after Thailand’s Ministry of Industry notified the World Trade Organisation of these intentions, it amended this decision, to only apply to paraquat and chlorpyrifos. Luxembourg banned use of glyphosate from December 31, 2020 and the French government announced the cessation of use of glyphosate use by 2021. Marambe and Herath (2020) describe how regional restrictions on glyphosate were applied in Sri Lanka after late 2014. In Australia, many local councils have banned or are phasing out use of glyphosate as a weed control option and hazard signage often accompanies use of glyphosate in public spaces. In 2020, Kellogg announced that in its supply chains, it will phase out by 2025 wheat and oats treated with glyphosate as a drying agent.

A serious looming issue in the European Union is the re-registration of glyphosate due on 15 December 2022. It is possible that re-registration is not granted. Combined with EU directives to reduce Maximum Residue Limits (MRLs) to the limit for expired registrations, Australian export of crops such as canola to the EU that have late season glyphosate application could face a risk of rejection.

## Impacts of a Ban on Glyphosate

### Australian farm-level impacts: weed management

A ban on glyphosate would boost adoption of crop options not dependent on glyphosate. For example, if farmers lose access to glyphosate and therefore have no incentive to plant GT canola, then triazine and imidazoline tolerant canola or potentially glufosinate-tolerant canola would be more frequently grown. Farmers would also increase their use of other herbicides. Of concern, farmers initially will apply more paraquat, another substitute non-selective herbicide.

Paraquat is an alternative to glyphosate, yet it is much more toxic. The statistical measure of toxicity is the $LD_{50}$. It is calculated as the milligrams of a toxicant per kilogram of body weight required to kill 50 per cent of a large population of test animals (WHO, 2010). Paraquat’s $LD_{50}$ is 150 mg/kg whereas glyphosate’s $LD_{50}$ is 4,230 mg/kg (WHO, 2010). That is, paraquat is 28 times more toxic than glyphosate. Were glyphosate no longer available, paraquat, saflufenacil or reglone would be likely substitutes and glufosinate-tolerant crops would be more widely grown. The perverse situation would arise where, to lessen use of glyphosate, in some cases, the even more toxic herbicide, paraquat, would increasingly be used. When this behaviour becomes known, then it is very foreseeable that social and media pressure will arise to prevent the use of paraquat in agriculture, due to its known greater toxicity.

**Australian farm-level impacts: enterprise alteration**

At the farm level, the loss of use of glyphosate is likely to increase the unit cost of grain production (Böcker *et al*., 2020; Marambe and Herath, 2020), as glyphosate is a mostly highly effective, relatively cheap herbicide. A ban on the use of glyphosate would unleash input substitution in crop production and possibly alter the mix of enterprises on some farms. Farmers' profits from crop production would lessen in the absence of a similarly affordable and effective herbicide. The loss of access to glyphosate would likely have a cascade of substitution effects. GT crops would disappear from cropping systems. Greater investments in other forms of weed control or other herbicide tolerant crop varieties would occur. Gross margin relativities of crop and pasture-based enterprises would change, mostly to favour the latter. Noting there are regional differences in cropping intensity, there would be additional regional differences in the spatial and financial impacts of loss of access to glyphosate.

The higher costs of grain production, in combination with reduced yields in some circumstances (Kehlenbeck *et al*., 2016; Pardo and Martinez, 2019; Brookes and Barfoot, 2016) would likely lead to higher grain prices, mostly in states or regions whose main markets are domestic rather than export markets; and especially in years of low-volume local production. In turn, industries dependent on feed grains, not only intensive animal industries but also traditional mixed enterprise large scale farms in Australia, would be affected. In particular, within the typical livestock grazing systems of southern Australia there is an autumn feed gap, where feed availability from pastures and crop residues is low (Revell *et al.,* 2013). During this feed gap, livestock are typically fed supplementary grain (Revell *et al.,* 2013). As Australia's climate dries (Smith *et al.,* 2000; CSIRO & BOM, 2018), dependence on feed grains is likely to increase (Kingwell, 2019). Were glyphosate no longer available, and no similarly effective ways of controlling weeds that simultaneously facilitated dry seeding were available, then, due to lower crop yields and more expensive crop production, feed grain prices in Australia would increase towards import parity, raising the cost of supplementary feeding during autumn on mixed enterprise farms. In addition, the production of certain livestock products (e.g. eggs, milk, poultry and pork) that specifically depend on feed grains would become more expensive.

More expensive feed grains would especially affect Australian livestock businesses during periods of extended drought. During drought, animals that normally would be extensively grazed become more reliant on supplementary feed grains. If those grains are made more expensive due to an inability to use glyphosate, assuming no similarly cost-effective alternative herbicides are readily available, then a greater level of de-stocking would be likely. De-stocking, such as occurred during 2002 to 2008 in eastern Australia (Nossal *et al.,* 2009), generates a broad range of mostly adverse economic impacts (Hughes *et al*., 2019). Often, both producers and consumers are made worse off.

**Global impacts**

If a global ban on glyphosate were to be applied, what would be the food availability/food security implications? Farmers would need to find weed control substitutes, currently often more expensive and sometimes causing reduced crop yields (Kehlenbeck *et al*., 2016; Pardo and Martinez, 2019; Brookes and Barfoot, 2016) and, in some cases, also causing altered land use to achieve the next best preferred level of profit.

If glyphosate could no longer be used, GT crops could no longer be grown and Australia's main GT crop, GT canola, would have to be replaced by another form of canola, such as triazine- or imidazoline-tolerant canola or glufosinate-tolerant canola, or some other crop or pasture option.

The farm management outcomes of these various changes, when aggregated across farm populations, would produce crop supply responses of a type often depicted in economic texts as an upwards, leftwards shift in the supply of various grains. These supply responses have ramifications for grain prices and prices of products dependent on grains, best described by general equilibrium modelling (Brookes *et al.,* 2017).

Countries more reliant on either the production or importation of GT crops would be especially vulnerable. By contrast, countries like Australia with agricultural systems less reliant on glyphosate would be advantaged. This is an inference from modelling research of Stone *et al*. (2002) who examined the trade implications for Australia of the use of GM crops, mostly GT crops, in Australia. They concluded that use of GT crop technology in Australia would be limited.

Noting that most of the world's main traded feed grains, maize and soybeans, are GT crops, if use of glyphosate was banned globally, or if glyphosate tolerant weeds became an acute problem in major grain growing regions, it would be highly likely that feed grain prices would increase. Since glyphosate is a relatively cheap and effective herbicide, its removal would necessitate substitution decisions. Other more expensive chemicals and non-chemical control methods would be employed that would lessen crop yields or raise costs of production (Marambe and Herath, 2020; Böcker *et al*., 2020). Countries or regions that import sizeable amounts of feed grains, like China, Japan and South East Asia, would be disadvantaged.

Brookes *et al.'s* (2017) modelling of the global economic consequences of a ban on glyphosate suggests loss of GT crops would cause yield reductions in areas where these crops are grown. Producers of GT crops, mainly the United States and South American countries, would experience net welfare losses because of reduced yields and production, despite their gains in terms of trade as the prices of these crops increased. Countries like China, the European Union and Japan that rely on grain imports would be welfare losers, as their terms of trade would be reduced. Australia would reduce its production of GT canola and cotton, but Australia would not be as exposed to lesser grain production as forecast for North and South America who greatly rely on GT crops.

An inability to use glyphosate, by affecting the nature and costliness of grain production, could weaken global food security by lessening the volumes of grains and meat produced, and increasing their prices.

## Policy Implications for Australia

One policy implication for Australia, surrounding the heightened concern in the wider community about ongoing use of glyphosate, is to encourage research, information and industry strategy papers and discussion forums that aid the Australian farm sector prepare for the possibility of a ban on glyphosate. For farmers, McCabe (2020) points out: "It has been observed in research on media reporting that farmers' understanding and views regarding glyphosate may differ from those of their customers. Even if they do not share views on glyphosate health and environmental risks, they will not maximize value chain profits if they ignore these views in product development decisions." (p. 13).

Even if a ban on glyphosate is not applied locally, Australian use of glyphosate could still be restricted due to the policy actions of countries that import Australian grain. These importing countries could place a nil tolerance for detecting glyphosate or its residues in imported grain. The risk to shippers of having their Australian grain cargoes rejected due to chemical detection would necessitate grain being produced in Australia without reliance on glyphosate. Being forearmed with appropriate industry responses to any required cessation of use of glyphosate would help avoid costly inappropriate industry adjustment.

Another policy implication is to maintain support for evidence-based flows of information on glyphosate to government, industry and commerce regarding its advantages and disadvantages.

Already, media and public interest in glyphosate in Australia has caused glyphosate to be listed in the top-four chemicals of general interest on the website of the Australian Pesticides and Veterinary Medicine Authority (APVMA). Such has been the heightened social media interest in glyphosate that several local councils in Australian cities now ban use of glyphosate in public open spaces, as noted earlier (ABC, 2018).

Media attention was heightened by the airing of a 60 Minutes television program in late 2019. The story mostly highlighted the alleged dangers of glyphosate, with the team of journalists rejecting an offer by the APVMA to provide a full background briefing on glyphosate (AVPMA, 2019). The APVMA has re-stated that registered products containing glyphosate are safe to use according to label directions. The APVMA statement is based on a review of more than 1,200 scientific studies on glyphosate and is consistent with similar rulings from other international regulators, including the European Food Safety Authority, the European Chemicals Agency, the United States Environmental Protection Agency, and Canada's Pest Management Regulatory Agency.

The current public concerns about glyphosate, including views aired on the 60 Minutes program, mostly stem from a widely reported finding by the IARC (2015) who classed glyphosate as being probably carcinogenic to humans. Yet the assessment by the IARC was solely a hazard assessment that only measured the potential harm of glyphosate, not its likelihood of harm. The IARC determination excluded an exposure assessment; yet it is widely known among chemical regulators and risk management experts that the adverse risk associated with using any product is the combination of the hazardous nature of the product and users' exposure to the product. Often the low frequency of use of a chemical, the low concentration of the active ingredient, and instructions on when and how to use the chemical lessen exposure to the hazard of the chemical. The consideration of exposure risk was overlooked by the media reporting of the IARC (2015) report. Also overlooked was the fact that the classification into which glyphosate was placed included several other common substances such as red meat, coffee, bitumen, very hot beverages and emissions from practices such as burning wood in indoor heaters and high-temperature frying.

When determining the likely risk before registering a product, the APVMA (2019) considers "all relevant scientific information when determining the likely risk before registering a product. This includes considering the impact on human health and worker safety—including long- and short-term exposure to users, as well as environmental and animal health risks, and residues in food." Consistent with chemical regulators in other countries, the APVMA uses a risk-based, weight-of-evidence assessment, which considers the full range of hazards and risks—including studies of cancer risks—and how human risk can be minimised through instructions for use and safety directions. Accordingly, the APVMA deems that all glyphosate products registered for use in Australia are safe to use, provided they are used as per the label instructions.

The collation and review of science-based studies that underpins the APVMA regulatory decisions is a very different process, with different emphases, from that which underpins herbicide reporting in the electronic and social media. Yet these media often are important informational sources that influence people's perceptions; and the combination of these perceptions, along with facts, can affect policy decisions.

Although the scientific process helps uncover facts to support evidence-based policy there can be a suspicion that evidence might be used selectively, thus increasing the influence of self-interested or captured experts (Strassheim, 2017). Earle *et al*. (2012) reveal that trust in risk management is negatively related to risk perception. Hence, high public concern about a perceived risk issue (for example, nuclear power or glyphosate) is associated with distrust of the managers responsible for that issue; whereas where there is low public concern (medical uses of radiation) there is greater trust in risk managers (Slovic, 1993). Accordingly, Earle *et al*. (2012) propose a trust, confidence and cooperation model to facilitate policy design and implementation.

A key element in building trust, confidence and cooperation is formulating research, assessment and communication programs that are not solely the domain of scientists or subject matter experts. Fischhoff (2013) describes the required elements of such effective programs as including (i) subject matter specialists; (ii) risk and decision analysts who characterise choices and identify critical information; (iii) behavioural scientists who can characterise beliefs and values, and then design and evaluate effective communications, and (iv) communication practitioners skilled at conveying content and messaging. The behavioural scientists, in order to accurately characterise beliefs and values, must interact with a wide cross-section of the public and, in the case of agricultural chemicals, with chemical users and those who investigate the various ways those chemicals affect human health and the environment.

To construct effective research, assessment and communication programs that regulate use of chemicals and educate users of chemicals requires collaboration between disparate groups. Such collaboration is not easy to achieve. In the field of public health, Jansen *et al*. (2010) notes that connecting academic research, practice and public health policy is difficult. These authors found these three domains do not easily work together because they often emanate from independent niches or silos of activity. The same concerns could well apply to the public health issues surrounding chemical use. Yet, overcoming barriers to cooperation between different disciplines is essential to form effective cross-discipline networks that can foster and protect evidence-based policy for chemical use.

The weaknesses of Australia's system of the regulation and use of pesticides and veterinary medicines has been amply pointed out in a wide-ranging review by Matthews *et al*. (2021). This review identified several opportunities for improvement. Public trust in industry and public institutions seems to have eroded. They pointed out that: "Community attitudes, especially in urban Australia, to farmers' agricultural chemical use are becoming steadily more demanding. Human health and safety, animal health and welfare, environmental protection, and transparent public processes need to be, and be seen to be, taken very seriously." (p. iii). They concluded that: "there has been an absence of effective continuing dialogue between regulators, industry, users, and the community. Historically, engagement among the system's regulators, policy makers and the broader community has usually occurred on an 'as needed' basis." (p. 67).

Accordingly, Matthews *et al*. (2021) recommend important changes to the APVMA and make several other suggestions to maximise regulators' accessibility and responsiveness to external stakeholders. They request establishment of a formal stakeholder forum, a whole of system forum and formation of expert advisory panels. The APVMA was perhaps anticipating the findings of Matthew *et al*. (2021) as the APVMA's revised corporate plan (APVMA, 2020) identified the APVMA's need to increase its client and stakeholder engagement activities and then apply their feedback.

Greater engagement by the APVMA in combination with implementation of the other key recommendations of Matthews *et al*. (2021) should help secure and build greater trust in the APVMA's evidence-based policy response to chemical regulation in Australia. In the case of glyphosate, changes to the APVMA, complemented by other structural changes suggested by Matthews *et al*. (2021) should encourage a better-informed, evidence-based, social debate over the use of glyphosate and similarly beneficially affect policy actions by various arms of government and industry.

## Conclusion

An Australian government senate committee review (Rural and Regional Affairs and Transport Committee, 2019) heard evidence about some challenges facing continued use of glyphosate and concluded that “neither the government nor industry has contemplated a loss of access to glyphosate or the impact in Australia of a ban on glyphosate overseas." (p. 88). Hence, one of the useful contributions of this paper is a start to better informing the public and policy debate surrounding the use of glyphosate in Australian agriculture and more broadly.

This paper identifies policy, environmental and legal influences that affect the current and future use glyphosate in Australian agriculture. We also report the possible ramifications for Australian and global agriculture of a possible ban on the use of glyphosate. We identify that further use of glyphosate for control of weeds in Australia is principally likely to be affected by:

(i) the on-going emergence of glyphosate resistant weed populations that lessen the herbicide’s effectiveness;
(ii) climate change and its impacts on crop establishment practices, encouraging the use of dry sowing that promotes development of alternative weed control methods;
(iii) the availability of cost-effective chemical and physical alternatives to glyphosate; and
(iv) legal actions against sellers of glyphosate, adverse social media, a growing distrust of industry and government institutions, and resultant government regulation that in concert restrict use of glyphosate.

The most impactful scenario is a ban on the use of glyphosate in agriculture, with the removal of glyphosate generating a range of substitution consequences at farm, national and global levels that affect crop production. Mostly those production consequences are adverse for farm businesses and consumers, as grain production is made more expensive.

The loss of access to glyphosate would have a cascade of substitution effects. GT crops would disappear from cropping systems. Some farmers would initially increase their use of paraquat, a herbicide far more toxic than glyphosate. Alternative herbicide tolerant crop varieties would increasingly be sown.

If eventually farmers were banned from using glyphosate and then also paraquat, due to its toxicity, then the farming system ramifications become more serious. Greater investment in other forms of weed control would need to occur. Alterations in the relative profitability of various enterprises could favour a greater inclusion of pasture-based livestock enterprises in Australian mixed enterprise farming systems. Weed management would likely become more complex and expensive; at least until a cost-effective replacement to glyphosate was developed, but that may be several years away.

If a global ban on glyphosate use applied, then feed grains like maize and soybeans, whose production is mostly via GT technologies, would become globally more expensive if alternative crop technologies as cost-effective as GT technologies are not available. In relative terms, Australia would be advantaged as the feed grains Australia exports (barley, wheat) do not rely on GT technologies. Higher international grain prices in turn would trigger higher prices of agricultural commodities (e.g. eggs, dairy, poultry, pork) dependent on grain-feeding. Global regions greatly dependent on GT crops, either as producers or consumers, would be particularly disadvantaged. Those regions would include much of Asia, North America, and South America. Australia is not one of those regions to be so disadvantaged by a global ban on glyphosate.

The Australian policy implications of these findings are briefly discussed. The dearth of policy research papers that examine or propose government and industry strategies in response to a foreseeable abolition of the use of glyphosate is identified. Also, we stress the need to commit resources to ensure evidence-based flows of information about glyphosate to support policy actions by government and industry. In particular, we see advantage in implementing recommendations of Matthews *et al*. (2021) following their review of Australia's system of regulation and use of agricultural chemicals. Their recommendations are likely to help secure and build trust in the APVMA's evidence-based policy response to chemical use in Australia and ensure greater stakeholder engagement by the APVMA and other arms of government and industry.

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