

REVIEW

When toxic chemicals refuse to die — An examination of the prolonged mercury pesticide use in Australia

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Mercury, even in low concentrations, is known to cause severe adverse human health effects. In the early 1900s, mercury became a popular fungicide ingredient, leading to multiple poisoning incidents that forced much of the world to act upon phasing out mercury use in agriculture. These incidents spurred the advancement of mercury science and the implementation of international policies and regulations to control mercury pollution worldwide. Despite these developments internationally, Australia continued using methoxyethyl mercury chloride as a fungicide to treat sugarcane against the fungi *Ceratocystis paradoxa* (pineapple disease). At the request of the manufacturer and following pressure from Australian researchers and the Minamata Convention on Mercury, Australian authorities announced a ban on mercury-containing pesticide in May 2020. Australia's unique reluctance to act on controlling this hazardous pollutant makes it an interesting case study for policy inaction that runs counter to global policy trends and evidence-based decision making. As such, it can provide insights into the challenges of achieving multilateral agreement on difficult environmental issues such as global warming. In this review, I discuss the scientific development and policy decisions related to mercury fates and exposure of wildlife and humans in Australia to mercury used in pesticide. The historical uses of mercury pesticide and poisoning incidents worldwide are described to contextualize Australia's delayed action on banning and controlling this chemical product compared to other nations. Regulations on mercury use in Australia, which has not ratified the Minamata Convention on mercury, are compared to those of major sugarcane and pesticide producer nations (Brazil, China, Japan, India, Thailand, and United States) which have ratified the Convention and replaced mercury pesticides with alternative products. I discuss how mercury regulations have the potential to protect the environment, decrease human exposure to mercury, and safeguard the ban on mercury products. Ratifying the Minamata Convention would give Australia equal footing with its international counterparts in global efforts to control global mercury pollution.

Keywords: Great Barrier Reef, Shirlan, MEMC, Sugarcane, Fungicide, Mercury phasing-down, Mercury ban

Introduction

Mercury is a chemical element known for millennia due to its multiple uses throughout history. Archaeologists have shown that cinnabar, the common ore of mercury, was mined for mercury production more than 8,000 years ago in Turkey (Brooks, 2012). Throughout history, mercury was commonly used in a medicinal and industrial capacity. In ancient China, for example, mercury was thought to prolong life, heal fractures, and maintain good health. The Chinese used mercury (II) sulphide around 3,000 years ago to produce the red pigment vermilion (Langford and Ferner, 1999). In ancient Greece, mercury was used in ointments and for cosmetic purposes (Pawłowski, 2011).

The popularity of mercury as the remedy of choice as a treatment for syphilis and leprosy in Protestant Europe escalated between the 17th and 19th century (Rasmussen et al., 2008; Wong, 2016), even though its toxicity became well known through these uses (Langford and Ferner, 1999).

A more recent utility of mercury has been its effectiveness in controlling microorganism growth, leading to mercury becoming a popular fungicide in the 1900s (Booer, 1951; Kimura and Miller, 1964; Saha and McKinlay, 1973). Its popularity resulted in several unforeseen poisoning incidents, which brought into question its viability for continuing use. Currently, it is well known that mercury is a highly toxic metal with no known biological function in vertebrates (Crane et al., 2010). Regulatory agencies have recognized and reduced emissions worldwide, and the international Minamata Convention on Mercury has been established to manage mercury emission and limit pollution worldwide. At odds with the advance of knowledge on mercury's toxicity and with several nations who have replaced most mercury products with alternatives,

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methoxyethyl mercury chloride (MEMC) is still used as a fungicide in sugarcane plantations in Australia. The product registration was voluntarily canceled in May 2020 during the review of this article, meaning the product can no longer be produced in Australia, but existing supplies can be sold to, and used by, sugarcane farmers for the next year until it is fully banned (Australian Pesticides and Veterinary Medicines Authority [APVMA], 2020a; Schneider et al., 2020).

The subject of this review is (1) to examine the historical use of mercury compounds as pesticides in agriculture worldwide, (2) to evaluate the environmental and health incidents that led to advances in science and regulatory reform, (3) to review the current knowledge and gaps on mercury contamination from pesticide use in sugarcane plantations in Australia, and (4) to provide insights on why this toxic element was still recently registered in Australia to be used as fungicide in sugarcane crops. The prior use of mercury pesticides by the major agricultural countries (Brazil, China, India, Thailand, and United States) is discussed to provide relevant context for the decision Australia has taken to maintain mercury pesticide use up to 2020. This review culminates with the discussion of the important role of the Minamata Convention on phasing out mercury pesticides worldwide and the subsequent importance for Australia to ratify this Convention. As an example of global policy inaction in the face of strong scientific and policy pressure, the Australian continuing use of mercury provides a case study for policy inaction by other governments confronted by major environmental issues such as global warming.

Mercury properties as a fungicide and its usage in agriculture

Mercury has been used successfully in agriculture to protect seeds and plants from fungal diseases due to its effectiveness in killing spores, reducing fungal growth and biomass, and preventing the development of dormant mycelia, the vegetative part of a fungus (Gadd, 1993; Papagianni, 2004; Crane et al., 2010). Organomercurials, in comparison to other forms of mercury, have a pronounced fungicidal activity and were commonly used for seed dressing owing to their wide spectrum efficacy and very low application rates (Booer, 1951; Saha and McKinlay, 1973; Kramer, 1983).

The property of mercury as a fungicide was a remarkable discovery and paved the way for larger crop yields to support the growing world population (Booer, 1951; Smart, 1968). Mercury compounds were first used as fungicide in large scale in 1914 being applied as seed dressings to control seed-borne diseases of cereals in Germany (Smart, 1968). Uspulun, a chlorophenolmercury compound manufactured as a liquid dressing, became commercially available in 1915 by Bayer AG (a German multinational pharmaceutical and life sciences company; Smart, 1968). As the use of Uspulun proved to be very effective against plant pathogens, its usage quickly became popular (Tepper, 2010).

Mercury pesticide usage and popularity worldwide was at its apex in the 1960s (Fimreite, 1970; Huisingh, 1974;

Murphy and Aucott, 1999; Horowitz et al., 2014). In Canada, the use of mercury in seed treatments peaked in 1964, when approximately 16,000 kg of mercury was consumed for this purpose, corresponding to about 20% of that used in the chlor-alkali industry (Fimreite, 1970). In 1967, nearly 70% of all grain seed in Canada was treated with mercury compounds, equivalent to 13 million seeded acres (Fimreite, 1970), and the most frequently used mercurial treatments for seed dressing in Canada contained alkyl mercury (e.g., methyl mercury dicyandiamide [MMD]; Fimreite, 1970). In the United States, the peak in mercury usage for agriculture purposes occurred in 1956 (**Figure 1**), corresponding to 9.2% of the total mercury consumed commercially in the United States for that year (Murphy and Aucott, 1999).

Agriculture has not been a major mercury consumer when compared with other commercial applications such as the chlor-alkali industry (Murphy and Aucott, 1999). It is important to consider that its application as a pesticide, commonly in its organic form, releases this chemical directly into the environment by applying it to crops or soil (Murphy and Aucott, 1999). The organic form of mercury is more toxic than inorganic form as its absorption into the body is more efficient (Bernhoft, 2012). Even relatively small amounts of mercury pesticide can cause more significant damage to the environment than other major commercial uses of mercury (Horowitz et al., 2014).

Accompanying its success in increasing agricultural production, mercury's widespread use in agriculture came at a heavy cost to ecosystems and human health. These systemic health impacts, due to their severity, spurred a global scientific effort to advance practical knowledge of mercury toxicity on humans, wildlife, and food webs (Bakir et al., 1973; Derban, 1974; Dieterich et al., 1980). Several cases of mercury poisoning resulted from its use in fungicides (Elhassani, 1982). The initial major outbreaks were recorded in Iraq between 1956 and 1960, with the 1956 incident resulting in around 200 poisonings and 70 deaths; the 1960 incident resulted in 1,000 poisonings and 200 deaths (Jalili and Abbasi, 1961). Pesticides containing ethylmercury compounds were involved in both instances. In 1961, an additional mercury poisoning outbreak occurred in Pakistan due to human consumption of wheat grains treated with phenyl mercury acetate and ethylmercury chloride. About 100 people were reportedly affected and at least four people died (Haq, 1963). It is thought that, due to wheat being scarce at the time, mercury-treated wheat seed was bought for human consumption rather than for its intended use.

Despite these earlier mercury-poisoning incidents, mercury fungicide continued to be the standard in seed treatment, resulting in subsequent mercury poisoning episodes. In 1965, wheat seeds treated with the fungicide MMD resulted in 45 people being poisoned in Guatemala, of whom 20 died (U.S. Department of Health, Education and Welfare, 1966). In 1967, 144 cases of human mercury poisoning were reported in Ghana, including 20 deaths. Out of ignorance, the patients had ingested maize dressed with ethylmercuric chloride intended for sowing (Derban, 1974).

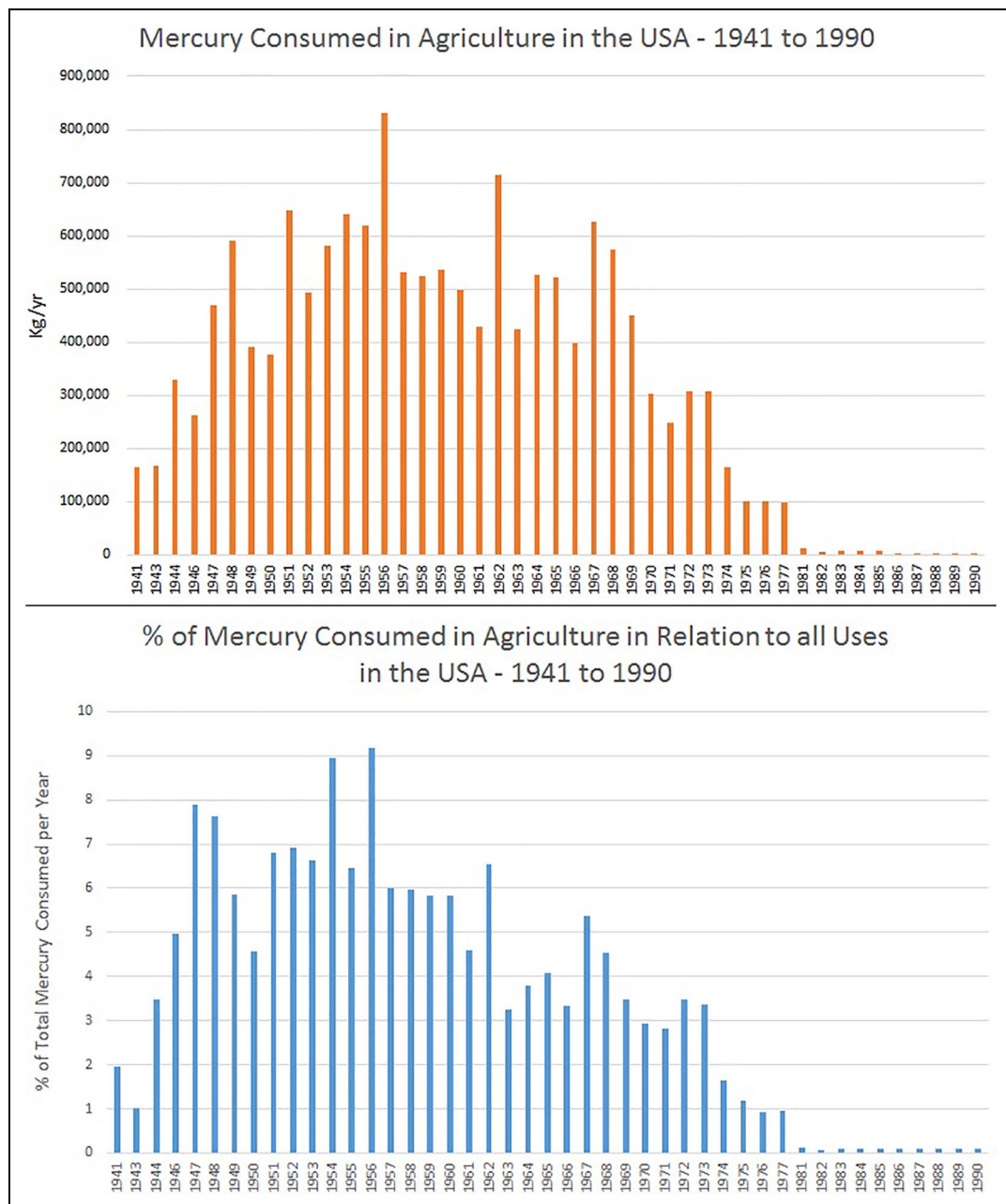


Figure 1. Mercury consumed in agriculture in the United States from 1941 to 1990. (A) Consumption in kilograms per year and (B) consumption of mercury in agriculture in relation to the total (Murphy and Aucott, 1999). DOI: <https://doi.org/10.1525/elementa.2021.053.f1>

The largest and most catastrophic ever-recorded mercury poisoning incident from agricultural use occurred in Iraq in 1972, when grain treated with alkyl mercury-based fungicide was imported to Iraq from Mexico and the United States (Bakir et al., 1973). The grain was intended for use as planting seed, not for human consumption. However, due to problems related to foreign-language labeling and late distribution within the growing cycle (i.e., it arrived after the sowing season), the toxic grains were instead consumed as food by Iraqi residents in rural areas (Al-Damluji, 1976; Al-Tikriti and Al-Mufti, 1976). More than 500 people died and more than 6,000 were hospitalized due to ingestion of bread made from seed grain treated with fungicide containing alkyl mercury (Broussard et al., 2002).

The link between mercury and human consumption was not isolated only to tainted seed consumption from agriculture. The possible hazardous nature of mercury residues in food was highlighted by a major mercury poisoning incident in Minamata city, Japan (Harada, 1995). In 1956, an organomercury compound was released as part of industrial wastewater in the Minamata Bay and the Shiranui Sea, resulting in mercury bioaccumulation and biomagnification in aquatic organisms, and ultimately in humans consuming them (Harada, 1995). This incident is the largest major mercury poisoning catastrophe in history, resulting in 2,265 victims (of which 1,784 people died; Japanese Ministry of the Environment, 2020). The symptoms associated with mercury poisoning became

Table 1. List of major agricultural and/or pesticide producer countries and actions taken to phase out the use of mercury pesticides. Accession, acceptance, or ratification has the same legal effect, where parties follow legal obligations under international law. Signature does not bear legal obligation and does not necessarily prejudge ratification. DOI: <https://doi.org/10.1525/elementa.2021.053.t1>

Country	Mercury Pesticide Usage	Minamata Convention
Japan	Banned in 1973	Ratified in 2016
Brazil	Banned in 1985	Ratified in 2017
United States	Banned in 1993	Acceptance in 2013 ^a
Thailand	Banned in 2005	Accession in 2017 ^a
China	Banned in 2010	Ratified in 2016
India	Banned in 2018	Ratified in 2018
Australia	Banned in 2020 ^b	Signed but not ratified

^aRatification, acceptance, approval, and accession are similar means by which a state establishes its consent to be bound by a treaty, depending on domestic legal or policy requirements. Accession has the same legal effect as ratification, acceptance, or approval and was opened from the day the Convention was closed for signature—on October 10, 2014. Unlike ratification, acceptance, or approval, which are preceded by signature to create binding legal obligations under international law, accession requires only one step, namely the deposit of an instrument of accession.

^bAustralia canceled the use of the last mercury pesticide product registered in the country during the review process of this article (Schneider et al., 2020). Existing supplies can be sold to, and used by, sugarcane farmers until May 2021.

known as Minamata disease. These include ataxia, numbness in the hands and feet, general muscle weakness, narrowing of the field of vision, and damage to hearing and speech (Harada, 1995). In extreme cases, insanity, paralysis, coma, and death follow within weeks of the onset of symptoms. A congenital form of the disease can also affect fetuses (Harada, 1995).

Studies following the above tragedies improved our understanding of the adverse effects of mercury on human health. Clinical manifestation and symptoms of mercury poisoning became clearer and easier to diagnose in humans (Tsubaki and Irukayama, 1977; Clarkson and Magos, 2006; Eto et al., 2010). In 1985, the acute reference dose (ARfD) was established for organic mercury by the U.S. Environmental Protection Agency (USEPA). ARfD is defined as an estimate of a substance in food or drinking water, expressed on body weight basis, that can be ingested over a short period of time, usually during one meal or one day, without appreciable health risk to the consumer based on all known facts at the time of evaluation (Solecki et al., 2005). The original ARfD of 0.3 µg/kg/day determined in 1985 was based on the Iraq mercury poisoning incident and Minamata disease (National Research Council, 2000). In 1995, the original ARfD was

lowered to 0.1 µg/kg/day and maintained after a detailed reassessment in 2002 (USEPA, 2002).

The 1972 Iraq incident also stimulated the creation of the Recommended Classification of Pesticides by Hazard established by the World Health Organization (WHO, 2010), first published in 1975. Mercury pesticides have been classified as “highly hazardous pesticides” by both WHO and the United Nations Food and Agriculture Organization (FAO). Both FAO (2020) and WHO (2020) refer to mercury threats to health and the environment and recommend that phasing out mercury pesticides should be an international priority.

The historical phasing out of mercury pesticides worldwide

Mercury-containing fungicides were banned in most countries in the 1970s and 1980s (Broussard et al., 2002) as a result of the mercury poisoning incidents described above. Most countries no longer allow these pesticides to be manufactured or marketed for crop protection due to their toxicity (UTZ, 2015; WHO, 2019). Countries that have not officially banned its use have either deregistered and or discontinued their use and Australia only recently in 2020 (APVMA, 2020b).

The phasing down/out of mercury pesticides occurred concurrently in both affluent and lower income nations (Table 1). In Sweden, a ban on the continued use of organomercurials was imposed in 1965 after populations of seed-eating and predatory bird species began to decline drastically due to mercury uptake through consumption of seeds treated with mercury (Huisingh, 1974). In 1966, Japan replaced mercury pesticides with nonmercurial options through an instruction from the Ministry of Agriculture and Forestry. By 1973, all commercial registrations for organomercury had lapsed (Ota, 2013). In the United States, several mercury compounds have been deregistered since the 1960s. The last mercury pesticide was deregistered in November 1993, when the manufacturer voluntarily canceled the registration of its product, which was used to control pink and gray snow mold (Table 1; Bingham, 1992).

Brazil banned all pesticides containing alkylmercury compounds in 1975 (Table 1; Ministério da Agricultura, Pecuária e Abastecimento [MAPA], 2020). Inorganic compounds of mercury were banned for pesticide use in the early 1980s (MAPA, 2020). In Thailand, the Ministry of Industry issued a notification list banning the use of hazardous substances in 2005, including mercury (Table 1; Thailand Ministry of Industry, 2013). China followed by banning mercury pesticide usage in 2010 (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2020). India banned mercury pesticides significantly later than most countries, in 2018 (Table 1; Ministry of Agriculture and Farmers Welfare, 2019), most likely encouraged by their ratification of the Minamata Convention.

Although mercury poisoning incidents around the world have caused extreme environmental and human health hazards, Australia has stood alone in maintaining the use of mercury pesticide to control fungal diseases in

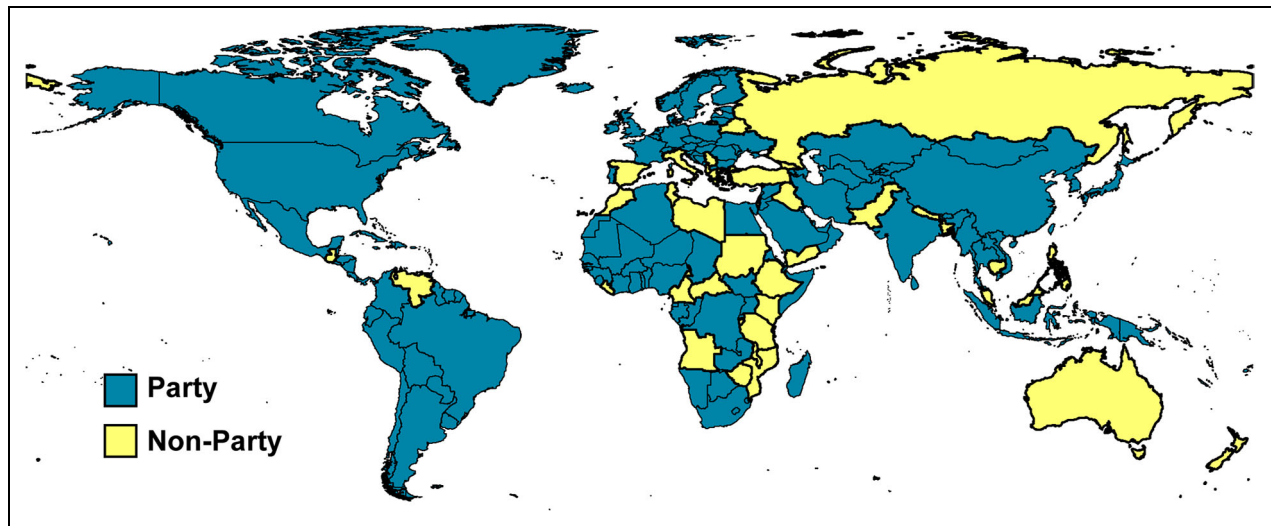


Figure 2. Party and non-party nations of the Minamata Convention on mercury as of May 2020. DOI: <https://doi.org/10.1525/elementa.2021.053.f2>

sugarcane plantations up to 2020 (Evers et al., 2017; APVMA, 2020b). Although Australia had moved to phase out most mercury-containing compounds, the decision to grant an exception to one product, Shirtan Liquid Fungicide[®], meant that mercury continued to be used in the Australian sugarcane industry. In July 1992, the Australian Agricultural and Veterinary Chemicals Council recommended revoking the clearances for mercury fungicides because of environmental concerns (APVMA, 2014). The main concern lay in the long-term persistence of mercury, which can result in it accumulating to unacceptable concentrations in soils, particularly where heavy and repeated applications are made (APVMA, 2014). Following this review, in 1995, the APVMA (2014; formerly the National Registration Authority for Agricultural and Veterinary Chemicals) canceled the registration and associated label approvals for agricultural products containing mercury, except for Shirtan Liquid Fungicide[®].

This exemption placed Australia's stance on mercury at variance with that of many countries, including its conventional international partners (e.g., Japan, the United States, Canada, and New Zealand). Despite having more pressing economic limitations, noncounterpart lower and middle-income countries (e.g., Brazil, China, India, and Thailand) have been far more effective in regulating and banning mercury products (**Table 1**). Lower- and middle-income countries are often less able than wealthy nations to pivot to new technologies due to a range of constraints, such as budget limitations, personnel shortfalls, agrochemical industry economics, complex laws, and government compliance regulations (Garcia et al., 2005; Pelaez et al., 2013; Snyder and Ni, 2017; Donley, 2019). In these countries, mercury's risks to human health and the environment were considered so significant that the socioeconomic barriers were overcome. In Australia, therefore, socioeconomic factors at the national scale cannot explain the retention of mercury pesticide use, leaving other factors as potential explanations.

The crucial role of the Minamata Convention in phasing out mercury-based products worldwide

Based on the substantial evidence of global adverse impacts from mercury and its compounds, an international treaty to control mercury pollution, the Minamata Convention on Mercury was established in 2013 (United Nations Environment Programme [UNEP], 2020). Named after the mercury poisoning incident in the Minamata Bay in Japan (Harada, 1995; Tsuda et al., 2009), this convention established further international action to reduce the risks to human health and the environment from the release of mercury and its compounds to the environment (UNEP, 2020). The Convention requires its parties (**Figure 2**) to adopt goals for the reduction of mercury emissions and releases.

The Minamata Convention plays a key role in phasing down the use of mercury products, including pesticides, as it imposes a full ban on this product to all parties equally, regardless of their economic status. Pesticides are subject to Article 4 of the Convention, which requires that manufacture, import, or export of pesticides be phased out by 2020 (UNEP, 2020). This has prompted countries to ban mercury pesticide use, for example, India, which imposed bans in 2018 when the country ratified the Convention (MGFW, 2019). Furthermore, the parties are required to report the measures taken to phase out mercury pesticides in the biennial report of the fourth Conference of the Parties in 2021, pursuant to article 21.

The Minamata Convention is also beneficial in avoiding any retreat from bans or from commitments to phase out mercury products. Its effectiveness is evident in the example of the current presidential administration in Brazil (under Jair Bolsonaro, elected in 2019), which reversed pesticide safeguards established under previous administrations (Abessa et al., 2019). However, mercury pesticides cannot legally be reintroduced in Brazil as the government is bound by the provisions of the Minamata Convention. Although countries could also withdraw from the

Convention, established global norms make it difficult for countries to have regulatory rollbacks or even changes to legislation.

The Minamata Convention has a tertiary effect that limits the ability of a non-party to manufacture mercury products. Countries that rely on the international trade of mercury to supply domestic needs will only be able to import mercury from the few countries that have not ratified the Convention (UNEP, 2020). Even if a country has not ratified the convention and continues to manufacture mercury products banned by the Minamata Convention, their production and distribution will be limited.

The UNEP Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, which entered into force in 2004, also may play a role in restricting the trade of mercury and its compounds if the laws of a given importing country restrict mercury trade. Although this treaty does not mandate a ban on mercury, it provides information to exporting countries that an importing country will not accept mercury through trade (UNEP, 2020). Many hazardous chemicals listed in the Rotterdam Convention, including mercury, are already banned in countries party to the treaty due to human and environmental health concerns.

The lack of countries to supply mercury to Australia has not limited mercury production domestically, as Australia currently has four mercury recycling facilities that meet domestic needs for mercury supply (Marsden Jacob Associates, 2015; Zaunmayr, 2018). This has caused a mercury self-supply resilience and economic inertia. The ratification of the Minamata Convention would be a significant step to reduce the production of mercury products in Australia. Despite having signed the Minamata Convention in 2013, as of 2020, Australia has not ratified it and no expected date has yet been indicated. Being a signatory does not prejudice ratification and does not bear legal obligation, but a willingness to consider being bound by the obligations of the treaty at a later date.

The long-term use of mercury-based fungicide in sugarcane crops in Australia: A review of the current knowledge

In Australia, MEMC was registered by the APVMA (2020b) until May 2020 for the control of pineapple sett rot of sugarcane, also known as pineapple disease. The disease is caused by the fungus *Ceratocystis paradoxa*, which proliferates under low temperature, excess or low soil moisture, and deep planting (Wismer and Bailey, 1989).

This mercury fungicide was manufactured and commercialized in Australia under the name Shirtan Liquid Fungicide[®], permitted for use in Queensland (QLD), New South Wales (NSW), Western Australia, and the Northern Territory (APVMA, 2020). It contains 120 g/L mercury present as MEMC and is only used for sugarcane plantations. This form of mercury is in the class of fungicides that offer the most serious health hazards (Derban, 1974; Lehotzky et al., 1988). As an organomercurial compound, it is efficiently absorbed through the skin and is readily

bioaccumulated by aquatic organisms and can cross the blood–brain barrier (Bigham et al., 2005).

Growers that use Shirtan[®] apply the chemical to sugarcane setts prior to planting. The yearly consumption of mercury used in agriculture is not available publicly from the APVMA. There are only two assessment and data reports on mercury emission from Shirtan[®] publicly available: the work of Johnson and Ebert (2000), which estimates 500 and 1,000 kg of mercury applied per annum between 1960 and 2000 in Australian sugarcane plantations, and a report produced for the Department of Agriculture, Water and the Environment (Marsden Jacob Associates, 2015) indicating 44,000 L of Shirtan[®] per annum was used between 2011 and 2014, an amount that would treat around 77,000 ha (77%) of cane. This corresponds to 5,280 kg of mercury being released into soils and river catchments that could potentially flow into the world's largest coral reef system: the Great Barrier Reef (GBR; Figure 3).

Mercury contamination in sugarcane soils

Most studies on mercury examining the concentrations of mercury in sugarcane soils in Australia were undertaken in the 1990s (Rayment et al., 1997; Rayment et al., 1998; Rayment et al., 2002) in the states of QLD and NSW (Table 2). As MEMC has been used as pesticide in sugarcane fields since 1953 (Johnson and Ebert, 2000), no baseline mercury concentrations were available for the studies mentioned above (Rayment et al., 1997; Rayment et al., 1998; Rayment et al., 2002). This makes it impossible to measure the low natural levels of mercury in Australian soils prior to the development of cold vapor atomic absorption spectrometry (Hatch and Ott, 1968). To overcome this issue, background concentration was estimated using “paired” sites of similar soil types with minimal or no history of sugarcane plantation (Rayment et al., 1997; Rayment et al., 1998; Rayment et al., 2002). The difference of mercury concentrations between soils from “paired” sites (with mercury concentration between 10 and 50 ng/g) and soils from sugarcane fields were almost 3-fold (Table 2).

Mercury concentrations in sugarcane soils were higher in NSW soil than QLD soils. The mean mercury concentration in NSW was reported as 160 ± 90 ng/g of mercury for soil depth 0–250 mm (Rayment et al., 1998), while in QLD, the mean mercury concentrations from several studies was approximately 76 ng/g (Table 2). The higher concentrations in NSW can be explained by the amount of MEMC applied in the region. Hamilton and Haydon (1996) reported a total of 400 kg of MEMC applied annually in NSW, which if distributed equally would equate to 15 g of mercury per hectare NSW. In QLD, it would equate to 3-g mercury per hectare (Hamilton and Haydon, 1996).

A more recent study offers a detailed evaluation of mercury in soil and water in the Tully River basin (Turull et al., 2018), where approximately 200 km² of sugarcane agriculture is grown on the floodplain. This study measured soil mercury concentrations from four sugar cane fields. Concentrations reached 264 ng/g ($\mu = 77 \pm 10$

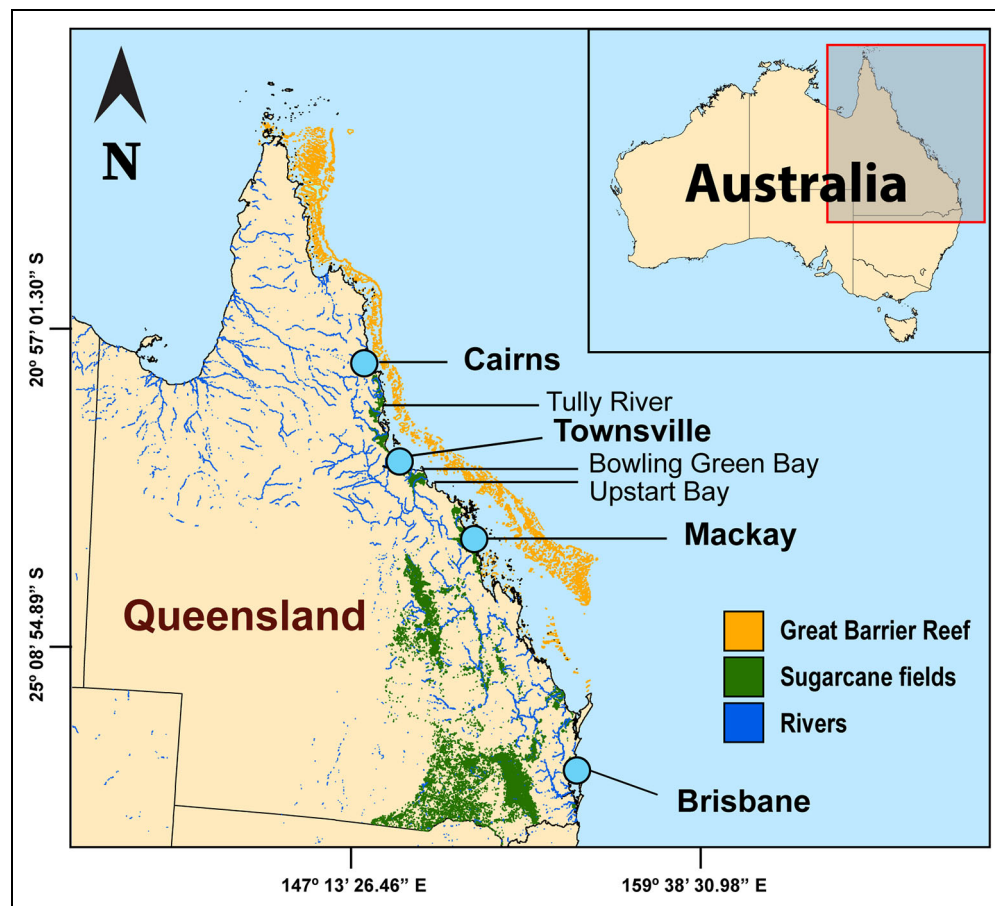


Figure 3. Sugarcane plantations (green) in Queensland, Australia, and sites mentioned in the text. In dark blue are the main rivers that could potentially drain mercury to the Great Barrier Reef (orange). Map layers from the Queensland Department of Environment and Science (Pringle et al., 2018; Crossman and Li, 2020). No publicly available map was found for sugarcane crops in New South Wales. DOI: <https://doi.org/10.1525/elementa.2021.053.f3>

ng/g at depth 100–200 mm; **Table 2**). Collectively, these soil studies indicate an average 3-fold increase in mercury concentrations compared to paired untreated sites (**Figure 4**).

The degradation of organic mercury in soil is a slow process (Kimura and Miller, 1964; Turull et al., 2018). A 35-day laboratory experiment applying methylmercury chloride (MMC) has shown that 86%–94% of the original MMC remained in the soil after the 35-day experiment period. The minute amount of inorganic mercury detected in soil and lack of mercury vapor indicated that methylmercury compounds are quite resistant to degradation in soil (Kimura and Miller, 1964; Chalker, 2017).

The above results do not agree with findings produced by Nufarm, the producer of Shirtan[®]. Although Nufarm complies with the regulations imposed on Shirtan[®], including sale restrictions and mercury monitoring in soils (Nufarm Australia Limited, 2017), Nufarm argues that results from their mercury monitoring in soil show no evidence that the use of Shirtan[®] in sugarcane leads to mercury accumulation in the soil (Marsden Jacob Associates, 2015). This contrasts starkly with the tripling of mercury concentrations found by independent researchers (Rayment et al., 1998; Rayment et al., 2002; Turull et al., 2018).

The above studies in Australia clearly show that mercury is likely to be accumulating in treated soils. Surprisingly, the APVMA has not reviewed these recent studies or not updated their chemical review document—the last chemical review was conducted in 1995 and the report has since been lost.

Mercury runoff from cane fields and water contamination

One of the greatest concerns in the use of MEMC in sugarcane plantations is the transport of organic mercury from soil to water streams via irrigation and rainfall. This organic form of mercury can be readily taken up by aquatic organisms, which can lead to toxicity (Lavoie et al., 2013). The leaching of MEMC from soil to water streams has been demonstrated in a field study assessing the fate of MEMC in sugarcane plantation soils in Australia, where significant movement of MEMC occurs from soil to rivers (Chalker, 2017). Once applied, MEMC resided predominately on the topsoil down to 22 cm below the surface, while below 22 cm, there was only trace mercury. However, most of the MEMC was mobilized from the soil with irrigation. The mercury level at all depths dropped by one order of magnitude over the first 5 weeks and likely was washed

Table 2. Mercury concentration (ng/g) in sugarcane soils in New South Wales (NSW) and Queensland (QLD) up to 2020. DOI: <https://doi.org/10.1525/elementa.2021.053.t2>

State	Location	Hg Concentration (ng/g Dry wt) Cane Field Soil by Depth					Source
		0–100 mm	100–200 mm	200–300 mm	0–250 mm	250–500 mm	
QLD	Rocky Point	84 ± 60			76 ± 58	50 ± 49	Rayment (2005) and Rayment et al. (1997)
	Maryborough	44 ± 30					Rayment (2005)
	Bundaberg	78 ± 50			20 and 90		Rayment (2005) and Rayment et al. (2002)
	Mackay	49 ± 20			20 and 50		Rayment (2005) and Rayment et al. (2002)
	Bunderkin	69 ± 40					Rayment (2005)
	Wet tropics	112 ± 60					Rayment (2005)
	Cairns				20 and 60		Rayment et al. (2002)
	Tully River basin	64 ± 76	77 ± 10	52 ± 42			Turull et al. (2018)
NSW		140 ± 50			160 ± 90	80 ± 40	Rayment et al. (1998)

Study sites reported in this table are known to grow sugarcane for at least 10 years. In Australia, sugarcane is a semi-perennial crop and individual fields are replanted approximately every 4–6 years. Sugarcane is planted by using cuttings, is harvested annually, and the root stock and base of the plant are left in place over the 4- to 6-year duration. Background Hg concentrations: Queensland and New South Wales = 10–50 ng/g (Rayment et al., 1998). Background values were based on non-sugarcane sites with similar soil.

Rayment et al. (1997; $n = 73$); Rayment et al. (2002; $n = 2$ for each site); Rayment (2005; $n = 103$).

into tailwater, primarily during the first irrigation sessions (Chalker, 2017).

Furthermore, a study in the Tully River Catchment, which receives inputs from sugarcane fields (**Figure 3**), has demonstrated that mercury runs off sugarcane soils into waterways and this process is intensified by heavy rain and flood events (Turull et al., 2018). All mercury water measurements downstream from sugarcane plantations exceeded the limit of 0.06 µg/L default guideline values recommended by the Australian water quality guideline to ensure 99% species protection level for slightly to moderately disturbed systems (Australian and New Zealand Guidelines, 2018). This result suggests that the Queensland Cane Growers Organisation's claim that "Shirtan Liquid Fungicide's use pattern in cane poses a negligible risk to human health and the environment" is an understatement (Canegrowers, 2017). No studies are available on the concentrations of mercury in sediments and aquatic organisms of any drainage basins comprising sugarcane fields. This is a gap in knowledge that requires immediate attention (**Figure 4**).

Mercury volatilization and atmospheric emissions from cane fields

The literature discussed above indicates that MEMC remains in the soil (Kimura and Miller, 1964; Rayment et al., 1997; Rayment et al., 1998; Rayment et al., 2002; Turull et al., 2018) and can be leached to water bodies through irrigation and rainfall events (Chalker, 2017; Willkommen et al., 2021). At the date of publishing, there are

no known studies in Australia demonstrating volatilization of mercury from the sugarcane soil surface across the soil–atmosphere interface.

Given that the long-term evaporation rate is dependent upon the type of soil and meteorological conditions (Schlüter, 2000), regional information is needed as international findings from other regions cannot be easily translated to QLD and NSW. Volatilization of MEMC from Australian soil may be contributing to air pollution and, thus, to the long-range transport of mercury by air and to the global pool of mercury emissions. Studies are needed to verify this pathway of mercury loss.

Mercury bioaccumulation and biomagnification through food chains

The potential for mercury bioaccumulation and biomagnification in terrestrial and aquatic food webs surrounding sugarcane fields has been understudied in Australia. No published research has examined the biomagnification rate of mercury in local food chains. This is of particular concern when considering that organic mercury is the form of mercury in pesticide used in Australia, which is readily accumulated in biota, particularly fish (Roberts et al., 2001). Mercury bioaccumulation and toxicity problems caused by mercury pesticides used in agriculture have been reported in other countries (Boudou and Ribeyre, 1997). In Sweden, mercury used in pesticide has been efficiently taken up by food web organisms (Lindqvist et al., 1991), and several bird species were in danger of extinction due to high mercury concentrations found

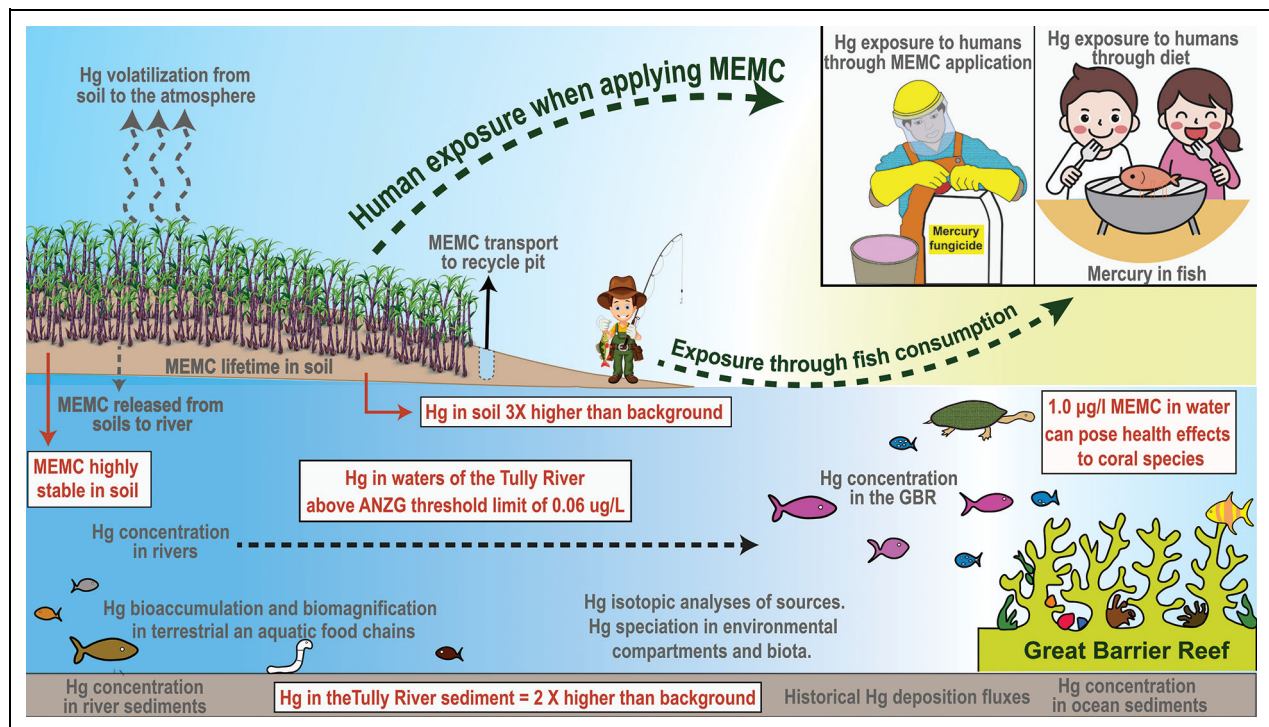


Figure 4. Mercury fates and processes where methoxyethyl mercury chloride (MEMC) fungicide is used to treat sugarcane setts in Australia. Brown text on white box represents current knowledge about the fates of MEMC in the Australian environment. Gray text represents MEMC knowledge gaps in Australia. The diagram represents a typical irrigation system with recycle pit but is not representative of all sugarcane field systems in Australia. Note the Great Barrier Reef is located at least 45 km offshore. DOI: <https://doi.org/10.1525/elementa.2021.053.f4>

in wild fauna, particularly in predator species (Lindqvist et al., 1991).

The failure of statutory authorities and industry to assess the potential pathways of wildlife and human exposure to organic mercury compounds over the last 60 years has put the Australian environment and population at risk of mercury contamination. Due to its toxicity, persistence in biogeochemical cycles, widespread distribution, and tendency to bioaccumulate (Gnamuš et al., 2000), a significant part of the 5,280 kg of mercury released in sugarcane soils per year is expected to have bioaccumulated and biomagnified up food chains. This is relevant to insect-based food webs in sugarcane fields: Insects are consumed by birds, fish, and other wildlife that are ultimately consumed by humans. Because of the many pathways linking terrestrial food webs with headwater streams (e.g., the dispersal of insects and amphibians with aquatic larvae; Gnamuš et al., 2000), the influence of mercury bioaccumulation from sugarcane pesticide may extend well beyond the sugarcane fields, and studies are needed to determine its extent.

Mercury in the Great Barrier Reef

As the Great Barrier Reef (GBR) is located at least 45 km east of the discharge of river catchments draining sugarcane fields (Cinner et al., 2016), the quantity of mercury released from sugarcane plantation that reaches the GBR is currently unknown. This lack of information is of concern when considering that the GBR is the world's largest

coral reef with over 3,000 individual reef systems and coral cays (Randall et al., 1997; **Figure 4**).

Currently, the few mercury studies conducted in QLD are restricted to estuaries and coastal areas, not specifically within the GBR. In the coastal areas of QLD, mercury has been measured in sediment cores of the Bowling Green Bay and Upstart Bay. The former is located just south of the estuary of the Burdekin River near a sugarcane plantation area (**Figure 3**). Mercury concentrations in the sediment of Upstart Bay were up to 100 ng/g in the 1990s, an order of magnitude higher than the average 50 ng/g background (Walker and Brunskill, 1997).

Besides mercury contamination from pesticides, historical artisanal gold mines in NSW and QLD should also be considered as a source of mercury in rivers, estuaries, and the GBR. A study investigating mercury concentrations in sediment cores collected in Bowling Green Bay (**Figure 3**) showed a sharp increase in the period between 1870 and 1890, related to the transport of mercury used in the amalgamation process of gold mining in the Charters Towers/Ravenswood area (Walker and Brunskill, 1997). The distinction between the two sources was roughly made by putting mercury concentrations into the time context. Artisanal gold mining in QLD occurred from the second half of the 19th century until the 1920s (Mate, 2014), but the use of mercury in gold extraction started phasing down in the 1970s, when cyanide became used extensively (Mudd, 2007). The use of MEMC in sugarcane plantations started in the 1950s, and later peaks in metal concentrations in sediment cores match the time frame

for the adoption of mercury fungicides. Further research is required to confirm this hypothesis. Modern isotopic analyses of mercury could support the distinction between gold mining and pesticides as sources of mercury in sediments of the NSW and QLD coast with greater precision. Most studies published on mercury in the region predate the 2000s, and, due to the limited analytical techniques available back then, mercury speciation and isotopic analyses are lacking. Dating techniques (Andersen, 2017) and mercury isotopic analyses (Hintelmann and Ogrinc, 2002) have significantly improved since then, opening the possibility of more precise pinpointing of mercury sources in the GBR.

Considering the amount of mercury released in the environment per year through pesticide use, and the ecological, world heritage, and tourism importance of the GBR, studies on mercury in this area are urgently needed to provide a full understanding of the sources and fate of mercury in this sensitive environment and its bioaccumulation and biomagnification into food webs (**Figure 4**).

Mercury toxicity to corals of the Great Barrier Reef

Mercury toxicity is of particular concern to the health of corals as it can denature proteins and inactivate a range of enzymes that are critical to metamorphosis in cnidarians (Leitz, 1997). In Australia, research has found that MEMC is extremely toxic to corals at low concentrations, affecting coral fertilization and metamorphosis, and causing coral bleaching and host tissue death (Markey et al., 2007). Several pesticides used in sugarcane plantation in Australia were tested in corals and MEMC caused the most deleterious health effects (Markey et al., 2007). MEMC affected all life stages of *Acropora millepora*, a common stony coral. Both fertilization and metamorphosis were inhibited, polyps became withdrawn, and photosynthetic efficiency was slightly reduced at 1.0 µg/L mercury. An MEMC concentration of 3 µg/L was usually enough to leave the *Acropora millepora* larvae motionless. At 10 µg/L MEMC treatment, branches bleached and some host tissue died. At a higher concentration of 30 µg/L, MEMC caused all larvae to rupture and die (Markey et al., 2007).

The concentration of MEMC in water causing inhibition of fertilization in 50% of the coral population within 144 h (EC₅₀) was 1.68 ± 0.04 µg/L (Markey et al., 2007). This, coupled with MEMC as low as 1.0 µg/L affecting all developmental stages of *Acropora millepora*, which are critical points in the life history of corals generally (Markey et al., 2007). The resulting failure of any single life stage event may reduce the capacity of populations to be replenished. This is a particular concern in the context of increasingly frequent coral bleaching events in the GBR, as well as the increasing magnitude of floods and bushfires in the region (Ainsworth et al., 2016).

No information is available for other aquatic organisms (**Figure 4**). This is key information to understanding how mercury is bioaccumulating and biomagnifying in local food chains. Given mercury is a persistent contaminant transferred from prey to predator (Schneider et al., 2020), measurements in organisms inhabiting sugarcane plantations, particularly top predators (snakes, raptors),

are important to understand how mercury from sugarcane fields poses a health risk to wildlife.

The potential health risks methoxyethyl mercury chloride (MEMC) can pose to farm workers

Several mercury compounds have been used in agriculture, and their toxicity is dependent on the chemical nature of the mercury compound (Saha and McKinlay, 1973). Metallic mercury ingested orally has relatively low toxicity due to low bioavailability, but chronic exposure to its vapor can be hazardous (Bidstrup, 1964). The soluble inorganic salts of mercury have been known to be toxic for a long time; however, organomercury compounds are even more toxic to humans than the inorganic salts (Saha and McKinlay, 1973).

Fortunately, cases of mass mercury poisoning like those catastrophic events seen in Iraq, Pakistan, and Guatemala are unlikely to occur in Australia. In those examples, mercury poisoning was linked to direct ingestion of organic mercury through consumption of mercury fungicide treated seeds (Al-Damluji, 1976; Al-Tikriti and Al-Mufti, 1976), while in Australia, it is used in sugarcane setts when planting crops (Kealley, 2015). The mode of exposure in these cases is different, and exposure specific to the Australian farm workers and the environment needs to be better assessed and understood.

In using MEMC in sugarcane plantations, cases of mercury poisoning may occur if a farm worker comes into contact with Shirtan[®] via ingestion or dermal absorption, either through the skin or orally. This is a concern as it is not uncommon for chemical users to apply or dispose of hazardous chemicals incorrectly (Calliera et al., 2013; Hui-ci et al., 2017; Bagheri et al., 2021). Although modern information and regulations imposed on the handling of mercury pesticides in Australia are comprehensive, they require workers to strictly follow procedures. This can be problematic if workers using Shirtan[®] are not trained to handle such toxic materials and are poorly supervised. This is a possibility in Australia when considering the widespread practice of hiring of itinerant farm workers, particularly those for whom English is not a first language. These workers will have to rely on their often limited English to appropriately follow technical safety procedures when diluting the MEMC concentrate.

The risk of mercury exposure increases when mechanical sett planters break down and farm workers must plant the cane setts manually. As well, mechanical planting sometimes requires manual intervention to complete the planting, with farm workers being sent out to plant the setts by hand (Kealley, 2015). In northern regions of Australia, where the climate is typically hot and humid, workers have been reported to remove protective clothing from time to time due to excessive perspiration. Direct exposure can occur by wiping their mouth or face with their hand (Kealley, 2015).

Another possible exposure to unsafe levels occurs when instructions to dilute the product are not closely followed. Farmers are known to “add a bit extra just in case” when diluting Shirtan[®], resulting in the diluted

treatment solutions containing a greater concentration of the organomercurial than instructed (Kealley, 2015).

Clearly, the above risks cannot be generalized. Most farmers are aware of mercury toxicity and care for the health of their workers. However, as mercury is toxic at low concentrations, any mistakes can harm the health of farmers. Industry practices and symptoms of long-term mercury exposure should be closely monitored by the government. The state Department of Health in QLD, Safe-Work NSW, and WorkCover QLD were contacted to provide information on mercury measurements in farmers, but the three agencies are not aware of any ongoing measurements. This is perhaps the most urgent information needed in relation to safety and health risks posed by MEMC use in Australia. To put this risk into perspective, the concentration of MEMC in Shirtan[®] is 120g/L, while the U.S. RfD for chronic oral exposure to methylmercury is 0.1 µg mercury/kg body weight/day. Any mistake made while using Shirtan[®] could represent a significant exposure to organomercury.

Difficulty in diagnosing mercury poisoning in farm workers

The misdiagnoses of mercury poisoning have been widely reported in the literature. In Guatemala, cases of mercury poisoning during the wheat growing seasons of 1963, 1964, and 1965 were originally thought to be viral encephalitis (Bakir et al., 1980). It was only after 20 people died following consumption of seeds treated with organic mercury that mercury poisoning was diagnosed (Bakir et al., 1973).

In the case of MEMC in Australia, mercury poisoning is unlikely to be acutely toxic. The likely symptoms are related to mild mercury poisoning, such as fatigue and mental slowness, and are unlikely to prompt farm workers to consult a physician. If medical assistance is sought, a medical practitioner is likely to point to more common causes, unless the possibility of mercury poisoning has been raised.

Difficulty in diagnosis is even more likely to occur with itinerant farmer workers who often move in between seasonal farming work or to other jobs for the rest of the year (Kealley, 2015). Most of the time, these workers do not have a constant or regular medical practitioner and may also lack clinical history on file. These workers, particularly those with limited schooling and language barriers, may not even realize that they have been exposed to mercury in the workplace (or do not understand the risks associated with mercury exposure) and are unlikely to give the medical professional any clues to possible mercury poisoning.

In addition to the difficulty in diagnosis, there is a latent period of weeks or months between exposure to organomercury and the development of poisoning symptoms. This latent period has been reported, studied, and proven to have magnified the problem of health effects from mercury exposure (Bakir et al., 1973; Al-Damluji, 1976; Al-Tikriti and Al-Mufti, 1976). In the Iraq poisoning incidents, patients admitted that they were warned against eating the wheat because it had been treated with

a harmful material (Jalili and Abbasi, 1961). Some of them washed it to rid it of the poison, and when they noticed that nothing happened to chickens that consumed it for a few days, they started eating it, sometimes mixed with larger amounts of untreated wheat or maize (Al-Damluji, 1976). Some people who had eaten the treated wheat remained well for some days or weeks, setting a poor example to others who did not hesitate to consume bread made from the mercury-treated wheat.

In Australia, this latent period between dose and the onset of symptoms may give farmers a false sense of security. This is particularly the case in areas where farmers employ itinerant workers during the months of planting and harvesting of the cane crop. By the time the symptoms appear, the worker will not necessarily remember that, back when they were working with MEMC, they were exposed to mercury (particularly considering the potential issues with memory and cognitive function, if they are symptomatic).

Given the toxicity of MEMC and the close contact of farmers, the most sensible solution would be for the government to initiate a health monitoring program with farmers using MEMC. In Australia, although farmers receive substantial practical information and management tools from governmental and nongovernmental agencies designed to assist producers in agricultural industries (Rural Industries Research and Development Corporation, 2007), mercury so far has not been officially considered a health risk to farmers in Australia (Fragar et al., 2001), and no biomonitoring program is in place to measure mercury concentrations in hair of farm workers during the time they are using MEMC. This leads to an infinite loop problem: If use of MEMC is not considered a health risk to farmers, no farm worker will be biomonitoring, and if a farm worker is not biomonitoring, the use of MEMC will never be considered a health risk to farm workers.

The summary of the current knowledge and the risks taken by Australia for maintaining the use of mercury pesticide up to 2020

As demonstrated above, the environmental fate of MEMC is not well-documented in the literature, and the ecological impacts and human exposure of MEMC are practically unknown in Australia. Despite the high toxicity of mercury pesticide already reported extensively in the scientific literature (Bakir et al., 1980; Clarkson, 2002; Bigham et al., 2005; Clarkson and Magos, 2006; Bernhoft, 2012), Australia still lacks a full understanding of the fate of mercury released from MEMC use in sugarcane, inclusive of the risks it may pose to aquatic organisms, humans consuming them, and farm workers applying the pesticides.

Although the chemical review of Shirtan Liquid Fungicide[®] would be expected to provide information about the ecological and human impacts of this product, the APVMA cannot locate this report. Furthermore, information on the quantity of MEMC used in agriculture per year is not available to the public. An attempt to access to this information via the Freedom of Information Act 1982 was refused by the APVMA on the basis they “are exempt under section 45 [documents containing material

obtained in confidence] of the FOI Act” and “refused access to documents under section 24A(1)(b)(ii) [Document lost or non-existent] of the FOI Act.”

Although there are comparable alternative products available (discussed below), the mercury-containing pesticide has substantial market penetration with approximately 80% of new plantings being treated, equating to an average of 44,000 liters of product per annum (Department of the Environment and Energy, 2016). This release of mercury via MEMC application in sugarcane plantations, through projected estimates of harm to human health per kilogram of mercury, is estimated to cost Australia approximately US\$25.8 million annually (Marsden Jacob Associates, 2015).

Figure 4 represents the MEMC cycle in sugarcane plantations in Australia. In brown are the information currently known (discussed above), and in gray are the gaps in knowledge that require immediate assessment to understand the environmental and health effects of the 5,280 kg of mercury released annually in Australia's sugarcane plantations.

The best studied environmental compartment is soil, while bioaccumulation and biomagnification are poorly studied and is the key gap that needs to be addressed to understand the exposure of mercury to wildlife and humans. There is also an urgent need for studies on the fates of different forms of mercury that cycle in the environment. Equally important is the clarification of the contribution of mercury from artisanal gold mining, which might be contributing mercury to river systems on top of sugarcane pesticide. The question of how 60 years of MEMC use in Australia has affected the environment and human health cannot be answered given the lack of knowledge and risk assessment for this product. However, it can be used as an example of a poor managerial decision that exposed Australia to considerable long-term risk, the consequences of which are still to be understood.

Political, industrial, and cultural impediments to a mercury pesticide ban in Australia

There are two reasons that can explain why MEMC has remained in use in Australia despite having been banned by multiple other peer regulatory agencies. First is MEMC's popularity as a fungicide, based on the belief that it stimulates rapid germination of cane setts in addition to controlling pineapple disease (Kealley, 2015; Marsden Jacob Associates, 2015). Second is the nonscientific claim that the use of MEMC in sugarcane in Australia poses a negligible risk to human health and the environment (Kealley, 2015; Canegrowers, 2017). A possible reason is the financial burden that phasing out MEMC will represent to a few, but powerful, Australian industries and companies. Countries far less wealthy than Australia have overcome much greater economic barriers to phasing out mercury pesticides.

The first reasoning that MEMC stimulates faster germination of cane setts has not been scientifically validated. The theory is likely a traditional belief over generations of MEMC users and an institutionalized cultural by-product rather than fact (Marsden Jacob Associates, 2015).

Pineapple disease, the pest that MEMC controls in Australia, is a disease threatening sugarcane worldwide. Mercury-free alternatives have already been tested overseas and in Australia, indicating that these alternative products are as efficient or better than MEMC (Bhuiyan et al., 2014; Apet et al., 2015). Researchers from other countries, like Brazil and India, have managed the disease without using mercury for years (Apet et al., 2015).

There are already alternatives to MEMC registered in Australia by the APVMA for the treatment of pineapple disease, some of which are cheaper (Marsden Jacob Associates, 2015). However, some farmers claim that these cheaper options will compromise germination of the setts requiring a greater expense of replanting (Marsden Jacob Associates, 2015). Nufarm argues that, if the mercury pesticide is not to be used, the risk to crops might be increased by 30% (Marsden Jacob Associates, 2015), equating to 3,150 hectares annually. Where crops are damaged, the most likely response is to replant the crop at a cost of AU\$1,000 to AU\$1,500 per hectare. Assuming this assessment is correct, the potential loss of not using MEMC could equate to AU\$3,937,500 per annum (Marsden Jacob Associates, 2015).

The possible negative effects on germination caused by mercury-free fungicide usage is not limited to Australia. Studies have shown limitation in germination due to use of certain fungicides, particularly for soy bean crops (Mertz et al., 2009; Zhang et al., 2010). In Brazil, farmers overcome this issue by mixing chemical groups of fungicides in the management of pineapple disease, with a lower dose of the group G1 fungicides (Russell, 2009). Brazilian farmers also mix biostimulants containing plant growth regulators with fungicides to ensure the germination of the sugarcane settings (W. L. Gavassoni, personal communication).

In Australia, alternative fungicides that are described as effective against pineapple disease are commercially available, including propiconazole, triadimenol, and flutriafol (Marsden Jacob Associates, 2015; APVMA, 2020b). Previous analysis indicated that propiconazole-based fungicides cost approximately half that of the mercury-containing pesticide and these relative costs were confirmed in discussions with the industry (Marsden Jacob Associates, 2015).

A true problem that can be considered is that fungi can develop a tolerance to the product and alternative pesticides can become less effective over time. This issue has been addressed by implementing pesticide resistance management plans, ensuring that products are used appropriately to manage resistance without sacrificing disease control (Anderson et al., 2019). To this end, the lessons taken by other countries that are important producers of sugarcane and have had mercury pesticides banned years ago could support farmers in Australia to move to mercury free options.

The argument that “MEMC poses negligible risk to human health and the environment” (Canegrowers, 2017) is not based on any evidence and contradicts the evidence currently available (Al-Damluji, 1976; Lindqvist et al., 1991; Turull et al., 2018). MEMC is a toxic fungicide,

and there are not enough studies on the impact to the Australian environment (discussed above) to provide evidence that the environment is protected.

An important point in the history of mercury use as a pesticide in Australia remains unclear in this review. In 1995, the APVMA canceled the registration and associated label approvals for farming products containing mercury with one exception, Shirtan[®] Liquid Fungicide, and *only if mercury concentration in the soil does not exceed background levels* (Turull et al., 2018). Questions that were to be addressed but remain unanswered are as follows: (1) Why did only Shirtan remain registered in Australia? and (2) why was the scientific information generated since the 1990s, demonstrating a 3-fold increase in mercury in sugarcane soils (Rayment et al., 1997; Rayment et al., 1998; Rayment et al., 2002; Turull et al., 2018), insufficient for the APVMA to phase out Shirtan[®]?

There are several other unknown factors that the Australian government has not acted upon to phase out MEMC. These could involve a range of factors such as existent Shirtan[®] stock, costs, cultural, and generational beliefs among others. Although the precise explanation is not clear, the risk the Australian Government has taken in maintaining the use of MEMC will hopefully be superseded by environmental and health awareness.

Conclusion

It is historically understood that mercury fungicide was a breakthrough discovery, contributing to greater agricultural productivity in many nations around the world. This early success has perhaps contributed toward a tendency to overlook its toxicity. Several incidents of mercury poisoning were recorded in the mid-20th century, but little changed until the 1970s when a major mercury poisoning incident took place in Iraq. Since these incidents, the diagnosis and treatment of mercury poisoning have improved markedly, and policies and regulations were implemented to control mercury pollution worldwide. Mercury pesticides have since been classified as *highly hazardous pesticides* by both the WHO and the United Nations FAO, and the United Nations Environmental Programme oversees an international treaty, the Minamata Convention on Mercury, to control mercury pollution and its exposure to humans.

Studies on the fate of MEMC applied in sugarcane in Australia are lacking, but the few studies available have shown a 3-fold increase in mercury concentration in soil and mercury concentrations in freshwater above guidelines. These results contradict previous claims that MEMC poses a negligible risk to human health and the environment. Extensive research has shown compelling evidence that mercury, even in low levels, is toxic. There is every reason to believe that MEMC use in Australia has placed the health of Australian wildlife and human populations at risk of long-term harm. Ratifying the Minamata Convention on Mercury would be a significant step forward on banning mercury pesticide and controlling mercury pollution, both domestically and internationally.

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Competing interests

No conflict of interest is declared for this article.

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