Safeguarding Australian exports of logs from future withdrawals of methyl bromide: A review of phytosanitary treatments

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Abstract

Australian log exports currently depend on the fumigant methyl bromide to meet the phytosanitary requirements of major importing countries, such as China and India. However, due to its ozone-depleting properties, use of methyl bromide in Australia faces potential restrictions and phase-out in future. Consequently, Australia requires alternative phytosanitary treatments that are both efficacious against pest species and economical for log treatment. This review consolidates and evaluates scientific literature on potential alternatives to methyl bromide for log export from Australia. The advantages and disadvantages of each treatment are discussed.

Ethanedinitrile, phosphine, sulfuryl fluoride, and methyl iodide show the most promise as alternatives to methyl bromide for industry. Ethanedinitrile is nearing commercial adoption, but improved communication and coordination between the chemical distributor and industry stakeholders regarding cost, application, and logistics are essential. Phosphine is an attractive option due to its low cost, but more data is needed to demonstrate its effectiveness against pests to facilitate potential approvals from international biosecurity agencies. Sulfuryl fluoride is approved by China for the disinfestation of Australian logs, is cost-competitive, and effective against target pest species. Nonetheless, its classification as a greenhouse gas (over 4,000 times more potent than CO_2) raises concerns about potential future phase-out. Methyl iodide serves as a direct replacement for methyl bromide, but additional research is necessary to establish appropriate application rates for pest control and to understand the cost implications of those rates. Addressing these research gaps through future research, development, and extension (RD&E) is crucial to maintaining access to export markets and enhancing industry resilience against future withdrawals of fumigants.

Table 1. Summary of current and potential phytosanitary treatments for export logs from Australia.

Treatment	Efficacy against pest species	*Safety and Environmental Risks	Registration in Australia	Acceptance by trading partners	Cost of product ($AUD/m³)
Methyl bromide	Highly efficacious against numerous pest species.	Australia is committed to seek alternative treatments to methyl bromide due to its powerful ability to degrade stratospheric ozone.	Registered for use, including ship hull fumigations.	Accepted by all major trading partners, including India and China.	$0.96 Costing based on a rate of 64 g/m³.
Ethane dinitrile	Highly efficacious against over 20 pest species of logs. Detailed data is available. Extensive number of research trials conducted.	The product is flammable. However, operation guidelines are available to reduce the risk of fire.	Registered for use, including ship hull fumigations.	Accepted by Malaysia and South Korea. Acceptance by India is pending. Not currently accepted by China.	$1.60 – 4.16 Cost not confirmed.
Sulfuryl fluoride	Highly efficacious against several pest species of logs. Commercial scale trials are lacking.	Greenhouse gas (>4000 times greater than CO_2). Chemicals with similar compositions (e.g., CFC 11) have been phase-out worldwide.	Registered for use, not including ship hull fumigations.	Accepted by China. Not currently accepted by India.	$2.88 Costing based on a rate of 80 g/m³.

		Considerable risk of future withdrawal.			
Phosphine	Limited efficacy data is available. Commercial scale trials are lacking. Increased insect resistance to the product is apparent in other industries (e.g., stored grain).	The product is flammable. However, operation guidelines are available to reduce the risk of fire.	Not registered for use in Australia to treat logs.	Not currently accepted by India or China.	$0.70 Cost based on the current treatment of logs in New Zealand for export to China.
Methyl iodide	Highly efficacious against several pest species of logs. Commercial scale trials are lacking.	No apparent risks in addition to its toxicity.	Registered for use in soils in Australia but not yet for logs.	Not currently accepted by India or China.	$1.50 - 3.50 Costing based on preliminary data and current cost of active.
Heat	Highly efficacious against pests. Limited efficacy data available for specific pests of logs. Commercial scale trials are lacking.	No apparent risks.	Available for use in Australia, no chemical registration required.	Accepted by China and India, though heating requirements vary.	>$27.00 (dry heat) Costing based on quotes for dry heat treatment of logs.

Bark removal	Thought to be efficacious against specific insect pests. Efficacy data is greatly lacking.	No apparent risks.	Available for use in Australia, no chemical registration required.	Accepted by China, though additional treatments (i.e., methyl bromide fumigation) are required if pests are discovered post debarking. Not accepted by India.	$6.50 Not published. Based on quotes provided to industry.

*All chemical treatments are highly toxic to humans. Strict operational procedures must be enforced (e.g., use of appropriate PPE) for all treatments, as described on the product label.

1.0 Introduction

1.1 Biosecurity and Australian log export

Biosecurity is a set of measures and practices designed to prevent the introduction, establishment, and spread of harmful pests and diseases that can adversely affect agriculture, ecosystems, and public health. Pest species—encompassing mammals, insects, plants, fungi, and bacteria—can be transported within shipments and packages across national and state borders. Consequently, most countries and states regulate and monitor the movement of goods to mitigate the economic, cultural, and environmental risks associated with pest incursions (Manual of Importing Country Requirements https://micor.agriculture.gov.au/Pages/default.aspx, EEPL 2021). Further, phytosanitary treatments are often implemented to disinfest commodities and control target pest species. The terms "quarantine" and "pre-shipment" (QPS) use relate to the circumstances in which phytosanitary treatments are applied to commodities to control target pest species.

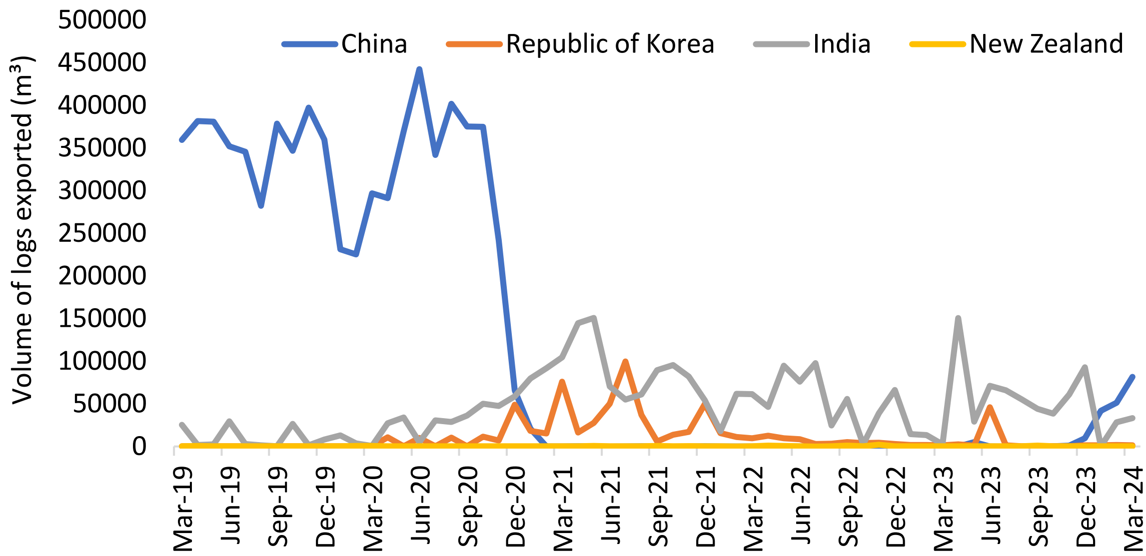
Quarantine applications are treatments to prevent the introduction, establishment and/or spread of quarantine pests (including diseases), or to ensure their official control, where: (i) Official control is that performed by, or authorized by, a national plant, animal or environmental protection or health authority; (ii) Quarantine pests are pests of potential importance to the areas endangered thereby and not yet present there, or present but not widely distributed and being officially controlled. Alternatively, pre-shipment applications are those non-quarantine applications applied within 21 days prior to export to meet the official requirements of the importing country or existing official requirements of the exporting country. Official requirements are those which are performed by, or authorized by, a national plant, animal, environmental, health or stored product authority" (The Ozone Secretariat 2007). By implementing effective QPS practices, countries can enhance their biosecurity measures and protect their agriculture and ecosystems from pest species. Therefore, phytosanitary treatments that are highly efficacious against a wide range of pest species and accepted internationally are crucial for facilitating global trade.

Many arthropods, including spiders, millipedes, and insects, commonly infest pine tree plantations in Australia. Certain insect species, particularly those that feed and reproduce within logs, cause significant damage to Australian forests each year. For instance, Sirex wood wasps (*Sirex noctilio*) burrow into trees to lay eggs and disseminate pathogenic fungi (*Amylostereum areolatum*), degrading timber quality (Neumann and Minko 1981). Other pest species, such as the five-spined bark beetle (*Ips grandicollis*), also inflict substantial damage on Australian plantations annually

(Gitau *et al*. 2012). Importers of Australian logs demand that all shipments be free of these pests to facilitate trade.

In 2023, Australia exported over 990,000 m³ of softwood and hardwood logs, valued at approximately $182 million (Australian Bureau of Agricultural and Resource Economics and Sciences). Over the past five years, China (63%) and India (24%) have been the primary importers of logs from Australia, though the export market has been highly volatile over the last five years (Figure 1). Most of these exports to China and India consisted of softwood logs (>90% *Pinus radiata*) sourced from South Australia, Victoria, Queensland, and Tasmania. Due to potential presence of insect pests within logs, both China and India require pre-shipment treatment of logs from Australia to ensure that all potential insect pests are controlled (Manual of Importing Country Requirements https://micor.agriculture.gov.au/Plants/Pages/India_IN/Pinus_spp1.aspx, https://micor.agriculture.gov.au/Plants/Pages/China_CN/All4.aspx). For the past several decades, fumigation with methyl bromide was and remains the standard phytosanitary treatment for log exports from Australia.

Figure 1. Volume of logs exported from Australia to other nations over a five-year period (Data provided by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).



1.2 Methyl bromide

Methyl bromide is a highly toxic compound that effectively controls a broad range of pests. The relatively high vapor pressure (i.e., the force of the gaseous molecules during transition from a liquid to a gas) of methyl bromide (190 kPa at 20°C) allows the fumigant to penetrate deep into commodities (e.g., wood, grain, soils, etc.). Fumigation with methyl bromide is internationally recognised as an effective treatment for the eradication of pests within wood, grain, cotton, hay, fruits, vegetables and many other products (Cox 2017). Therefore, many countries and states mandate the use of methyl bromide for QPS (Cox 2017). Internationally, QPS treatments using methyl bromide are regulated under two different treaties (The Ozone Secretariat 2007).

Methyl bromide was registered as a fumigant in Australia in 1945 and has since been used for QPS and soil fumigation (APVMA 2007). However, in 1987 an international agreement, known as the Montreal Protocol (signed by 197 countries), was formed to reduce the use of substances that deplete the earth's ozone layer, including methyl bromide (DAWE 2019). Methyl bromide is 60 times more powerful at destroying stratospheric ozone than chlorofluorocarbons (CFCs). Australia entered the agreement in 1989 and, in accordance with the Protocol, phased-out the use of methyl bromide in 2005 for all non-QPS treatments (e.g., soil fumigation), except where critical use exemptions were granted by the United Nations (Mattner 2012, DAWE 2019). QPS fumigation with methyl bromide is currently not regulated under the Montreal Protocol in 1992 because of its critical importance in sustaining international trade. However, countries are required to report their use of methyl bromide for QPS and advised to seek alternative treatments (Intergovernmental Panel on Climate Change https://www.ipcc.ch/). Recently, the United Nation's Methyl Bromide Technical Options Committee was tasked with reviewing the use of methyl bromide for QPS purposes. This is an important indicator that future uses of this fumigant may come under increased scrutiny and regulation under the Montreal Protocol.

Between 2019 - 2023, Australia used 433 - 793 tonnes of methyl bromide for QPS uses p.a., the fourth largest use of any country in the world, and considerably more than what Australia phased out for non-QPS uses. By comparison, the European Union ceased use of methyl bromide for QPS in 2010, and other countries like New Zealand mandate the recapture and destruction of the compound (UN environmental programme, ozone secretariat https://ozone.unep.org/). These discrepancies have amounted to growing political pressure on Australia to reduce its use of methyl bromide for QPS. However, to maintain Australia's biosecurity and international trade relations, alternative phytosanitary treatments to methyl bromide of equal or greater efficacy are required.

Log exports, primarily those to India and China, are the largest contributor to Australia's use of methyl bromide (e.g., 74% of all methyl bromide use in 2020, estimated 600 metric tonnes, Lee-Steere 2022). Increasing political pressure from the United Nations and the potential withdrawal of methyl bromide under the Montreal Protocol for all QPS uses pose significant risks to Australia's log export sector. To enhance resilience against the possibility of losing access to methyl bromide, industry urgently needs to explore and, at least partially adopt, alternative phytosanitary treatment options.

1.3 Current phytosanitary requirements for export of logs to India and China

China and India both require Australian exporters to obtain a phytosanitary certificate prior to shipment of logs. As of 2024, India requires that all log imports (*Pinus* spp.) originating from Australia are heat treated or fumigated with methyl bromide (Table 2). Treatment with methyl bromide is the industry standard and current export procedures and costing structures are based on this treatment. It is technically possible to heat treat (dry heat) logs for export in Australia, but the cost is exorbitant (>1700% more than methyl bromide). Therefore, Australian exporters do not consider heat treatment of logs to be economically viable (personal communication R. Brooks, Pacific Forest Products).

China requires that all logs sourced from Australia are heat treated, fumigated with methyl bromide or sulfuryl fluoride, or soaked in water for 90 days, prior to export (Table 2). In addition, China increased the application rate/s of methyl bromide for the treatment of logs in 2024 by ~90%. This rate increase will dramatically increase Australia's use of methyl bromide, and increase international pressure to find alternatives. Industry is currently evaluating the economic viability of these new rates and continued trade of logs into China (personal communication R. Brooks, Pacific Forest Products).

Treatment of logs with sulfuryl fluoride is not the preferred option by Australian exporters, primarily due to cost (Table 1). However, it is currently under consideration to replace methyl bromide in select circumstances (e.g., it is more cost effective at lower temperatures (10-15°C) than methyl bromide for shipments to China) (Table 2, personal communication R. Brooks, Pacific Forest Products). Soaking logs in water for 90 days is not considered economically viable by industry due to the relatively long treatment time, cost, and initial investment in infra-structure (e.g., holding tanks). Therefore, nearly all export logs from Australia destined for China are currently treated with methyl bromide.

Table 2. Phytosanitary treatments accepted by India and China for the importation of Australia logs (*Pinus* spp.).

Importing country	Treatment	Rate (g/m^3)	Core wood temperature (°C)	Duration (hours)	Cost of product ($AUD)/ m^3
India	Heat	n/a	56	0.5	>$27.00
	Methyl bromide	40	>21	24	$0.60
		56	16 – 20	24	$0.84
		64	11 – 15	24	$0.96
		72	10	24	$1.08
China	Heat	n/a	71.1	1.25	>$27.00
	Methyl bromide	80	>15	24	$1.20
		120	10 – 15	24	$1.80
	Sulfuryl fluoride	104	5 – 10	24	$3.74
		80	>10	24	$2.88
	Soak in water	n/a	n/a	2160	>$5.00

* The costs of all treatments are variable and difficult to quantify due to additional associated costs (e.g., labour costs, input costs, etc.).

2.0 Methyl bromide alternatives

Log exports from Australia are currently reliant on the availability of methyl bromide (see above). Any change in international regulations on the use of methyl bromide (recapture, phase-out, or withdrawal) for QPS would threaten market access of logs to importing countries. Therefore, industry urgently requires a range of alternative treatments. The adoption of any alternative phytosanitary treatment depends on several factors, including its efficacy against specific pest species, environmental impact, human health risks, registration for use in Australia, effects on wood quality, acceptance by trading partners (e.g., India and China), and cost. This review aims to compile and evaluate the leading options for phytosanitary treatments of logs for export. This work is required to identify the technical gaps and future RD&E needed to support adoption of these alternatives by industry. Through this review, ethanedinitrile, sulfuryl fluoride, phosphine and methyl iodide emerged as the alternatives with the greatest efficacy against target pest species, cost efficiency and acceptance by trading partners.

2.1 Ethanedinitrile

Ethanedinitrile (EDN) was first researched and developed as a fumigant in Australia (Waterford and Smith 2005). It is highly toxic to diverse groups of pests and has been used for disinfestation across a variety of materials, including soils, stored grains, and logs, for both QPS and non-QPS applications (Lee-Steere 2022, Armstrong *et al*. 2014). Due to its high vapor pressure (520 kPa) and volatility, EDN evenly distributes throughout treatment areas and effectively penetrates wood products (Ren *et al*., 2011). Ethanedinitrile has a higher rate of sorption into logs compared with methyl bromide, with an expected 82% drop in concentration from the initial dose rate within 10 hours of treatment (Hall *et al*. 2015). Unlike methyl bromide, EDN does not contribute to the degradation of stratospheric ozone. However, its flammability necessitates additional operational safety standards compared to those required for methyl bromide.

A comprehensive series of studies have demonstrated the efficacy of EDN against a range of pests and pathogens of forestry products, particularly relating export logs (Table 3). These studies have focused on key insect, nematode, and fungal species which are of significant concern to Australia's trading partners. Findings indicate that EDN is highly effective against these pests, and provides equivalent or better control than methyl bromide. Furthermore, commercial trials conducted in Australia and New Zealand in ship hulls have demonstrated EDN is highly effective against timber pest, pathogens and nematodes at or above 5^{o}C pests in logs (Najar-Rodriguez *et al*. 2020; personal communication K. McConville, Draslovka).

EDN is currently registered for use in Australia, including its application for treating logs within ship hulls to control numerous pest species. However, it has not yet been accepted by India or China for pre-shipment treatment of logs from Australia. Ongoing negotiations between Indian government officials and Draslovka, the registrant of EDN, aim to address this issue (personal communication S. Thalavaisundaram, Draslovka). Notably, EDN is registered for pre-shipment treatment of Australian logs destined for Malaysia and South Korea. Further, the Malaysian authority has approved EDN treated logs within ship hulls exported from Australia. However, over the past five years, Korean and Malaysian exports have only represented ~5% of the Australian export log market (data sourced from the Australian Bureau of Agricultural and Resource Economics and Sciences).

There are disparate estimates of the cost of log treatment with EDN, depending on whether they are sourced from the chemical company or industry (ranging from \$0.64 to \$3.20/m³ more than methyl bromide). Effective communication between Draslovka, fumigators, and industry stakeholders is essential for accurately assessing the economic and logistical needs of adopting EDN for the treatment of logs in Australia. This includes understanding requirements such as the need for more fumigant cylinders compared to methyl bromide fumigations.

Table 3. Summary of ethanedinitrile efficacy studies for control of forestry pest species. Each of these studies showed that ethanedinitrile was efficacious against the target species.

Pest Type	Species Name	Published Efficacy Studies
Insect	*Anoplophora glabripennis* (Asian long-horned beetle)	Dowsett & Ren (2007), Ren *et al*. (2006)
	Arhopalus ferus (Burnt pine longhorn beetle)	Pranamornkith *et al*. (2014), Najar-Rodriguez *et al*. (2015), Brash *et al*. (2007)
	Hylotrupes bajulus (House longhorn beetle)	Emery *et al*. (2014), Cermak *et al*. (2016)
	Monochamus alternatus (Japanese pine sawyer)	Park *et al*. (2014), Lee *et al*. (2017a), Lee *et al*. (2017b), Park *et al*. (2012)
	Tetropium fuscum (Brown spruce longhorn beetle)	Kumar *et al*. (2019)

Crypahalus fulvus (Minute pine bark beetle)	Cho *et al*. (2011), Park *et al*. (2021)
Dryocoetes autographus (Hairy spruce bark beetle)	Kumar *et al*. (2019), Stejskal *et al*. (2017)
Dryocoetes hectographus	Stejskal *et al*. (2017)
Hylastes ater (Black pine bark beetle)	Brash *et al*. (2007), Najar-Rodriguez *et al*. (2020)
Hylurgops palliates (Lesser spruce shoot beetle)	Stejskal *et al*. (2017)
Hylurgus ligniperda (Golden-haired bark beetle)	Brash *et al*. (2007), Najar-Rodriguez *et al*. (2020)
Ips typographus (European spruce bark beetle)	Kumar *et al*. (2019), Stejskal *et al*. (2017)
Pityogenes chalcographus (Spruce wood engrave)	Kumar *et al*. (2019), Stejskal *et al*. (2017)
Polygraphus poligraphus	Kumar *et al*. (2019)
Tomicus piniperda (Common pine shoot beetle)	Park *et al*. (2021), Park *et al*. (2007)
Hyphantria cunea (Fall webworm)	Park *et al*. (2021), Park *et al*. (2007)
Cryptotermes brevis (West Indian drywood termite)	Dowsett & Ren (2007)
Lasioderma serricorne (Cigarette beetle)	Ren *et al*. (2014), Ramadam *et al*. (2020)
Reticulitermes speratus (Japanese termite)	Cho *et al*. (2011), Park *et al*. (2021), Park *et al*. (2007)
Sirex noctilio (Sirex woodwasp)	Hall *et al*. (2023)
Sirex juvenus (Steel-blue woodwasp)	Aulicky & Stejskal (2019)

	Urocerus gigas (Giant woodwasp)	Aulicky & Stejskal (2019)
Nematode	*Bursaphelenchus xylophilus* (Pine wood nematode)	Cermak *et al*. (2016), Park *et al*. (2014), Lee *et al*. (2017a), Park *et al*. (2012), Stevens *et al*. (2022), Uzunovic *et al*. (2021), Seabright *et al*. (2020), Douda *et al*. (2020), Arbuzova *et al*. (2020)
Fungi/ oomycetes	*Diplodia sapinea* (Sphaeropsis blight)	Everett *et al*. (2023)
	Geosmithia morbida (Thousand cankers black walnut disease)	Uzunovic *et al*. (2021), Draslovka Technical Report (2019)
	Teratosphaeria cryptica (Eucalyptus leaf blotch)	Everett *et al*. (2023)
	Ceratocystis fagacearum (Oak wilt)	Uzunovic *et al*. (2021), Draslovka Technical Report (2019)
	Dothistroma septosporum (Red band needle blight)	Everett *et al*. (2023)
	Thyronectria fuckeliana (Canker)	Everett *et al*. (2023)
	Thyronectria pinicola	Everett *et al*. (2023)
	Grosmannia huntii	Everett *et al*. (2023)
	Grosmannia radiaticola	Everett *et al*. (2023)
	Leptographium procerum (White pine root decline)	Everett *et al*. (2023)
	Leptographium truncatum (Black stain root disease)	Everett *et al*. (2023)
	Ophiostoma floccosum	Everett *et al*. (2023)

Ophiostoma piceae (Vascular mycosis of oak)	Everett *et al*. (2023)
Phytophthora ramorum (Sudden oak death)	Uzunovic *et al*. (2021)
Phytophthora aleatoria	Everett *et al*. (2023)
Phytophthora citricola (Black hop root rot)	Everett *et al*. (2023)
Phytophthora cryptogea (Tomato foot rot)	Everett *et al*. (2023)
Phytophthora kernoviae	Everett *et al*. (2023)
Phytophthora pluvialis (Red needle cast)	Everett *et al*. (2023)
Lophodermium pinastri (Lophodermium needle cast)	Everett *et al*. (2023)

2.2 Sulfuryl fluoride

Sulfuryl fluoride is an odorless, non-flammable, and non-corrosive compound that rapidly diffuses and aerates. It has a boiling point of 55.2 °C and a vapor pressure of 1700 kPa at 21 °C, which is significantly greater than that of methyl bromide (Thoms 2010, Kenaga 1957). Sulfuryl fluoride effectively penetrates dense materials, including wood products, with low rates of sorption and without degrading them (Scheffrahn and Thoms 1993, Thoms 2010, Ren *et al*. 2011). For many decades, sulfuryl fluoride fumigation has been employed in the United States to manage structural pests, particularly termites, in residential settings (Armstrong *et al*. 2014). With the impending phase-out of methyl bromide in various industries worldwide, sulfuryl fluoride was evaluated, approved, and adopted by over a dozen countries, including Australia, as an alternative for disinfesting stored food products, such as grains, rice, and seeds, as well as mills and food processing facilities to control a range of pest species (e.g., *Tribolium castaneum*) (Mueller 2009, Armstrong 2014).

In Australia and several other countries, sulfuryl fluoride is registered for treatment of wood products, logs, and woodchips. The Australian label requirements specify a maximum application rate of 128 g/m³ over a 24-hour exposure period. China currently accepts sulfuryl fluoride, applied at a rate of 104 or 80g/m³ depending on the core log temperature, as a pre-shipment treatment of logs imported from Australia (Table 2). Notably, the cost of sulfuryl fluoride, applied at 80 g/m³, is comparable ($2.88) to that of methyl bromide (64 g/m³) ($0.96) for the treatment of logs in Australia (Table 2). Australian log exporters have advised that they are currently considering sulfuryl fluoride as an alternative to methyl bromide for shipments to China when core wood temperatures lie between 10 and 15°C (personal communication R. Brooks, Pacific Forest Products). Conversely, India does not currently accept sulfuryl fluoride for log treatment.

A review of the literature indicates that sulfuryl fluoride fumigation of logs and other timber products at rates equal to or less than 128 g/m³ can achieve total control of all tested insect pests and pine wood nematodes (Table 4). However, the number of pest species tested (19) are considerably less than that of EDN (43) (Tables 3 & 4). India has advised the Australian Department of Agriculture, Fisheries and Forestry that improved datasets, demonstrating the efficacy of sulfuryl fluoride against key pest species, would support its registration and approval for treatment of imported logs (personal communication R. Qaisrani; Australian Department of Agriculture Fisheries and Forestry).

Although sulfuryl fluoride does not degrade ozone, it possesses a high global warming potential (GWP) of approximately 5000 (Mühle *et al*. 2009). This means that impact of emissions of one tonne of sulfuryl fluoride are equivalent to more than 5000 tonnes of CO_2 on global warming. Chemicals with similar GWP values, such as CFC-11, have been phased out under the Montreal Protocol due to their contributions to global climate change (Lee-Steere 2022). While sulfuryl fluoride has not been targeted for phase-out under the Montreal Protocol, governments and industries are aware that its status may change in future, especially if global usage of the compound increases (Sulbaek Andersen 2009). There is strong potential that the sulfuryl fluoride will ultimately come under review through other international environmental protocols (e.g., The Paris Agreement).

Table 4. List of studies that assessed the effectiveness of sulfuryl fluoride fumigation for control pests of wood products. The species name and life stage (if applicable), the commodity, the fumigation parameters (temperature, rate, exposure time), and the proportion or probability of pest mortality are described for each experiment. Lethal dose (LD) and Probit probabilities indicate the estimated proportion of mortality achieved based on the application rate. A Probit 9 probability represents a mortality rate of 99.9968%. Symbols representing missing information (**-**) are included.

Pest species	**Source**	**Commodity**	**Life stage**	**Temperature (°C)**	**Rate (g/m³)**	**Exposure time (h)**	**Mortality (%) or Probability**
Ceratocystis fagacearum (wood-decaying fungi)	Tubajika & Barak (2011)	Wood blocks (birch, red pine, maple, poplar)	n/a	21±2	160	24	78.8
					160	48	93.9
					160	72	99.1
					240	24	95.6
					240	48	98.1
					240	72	100
	Seabright *et al*. (2017)	Northern pin oak logs (*Quercus ellipsoidalis*)	n/a	15.6	240	72	100
					280	72	77.8

					320	72	77.8
					128	96	58.3
					240	96	58.3
Arhopalus tristis (Burnt pine longhorn beetle)	Zhang (2006)	Sawdust from pine logs	Adult	15	15	24	100
					30	24	100
					60	24	100
					120	24	100
			Larva	15	15	24	99.3
					30	24	99.6
					60	24	98.9
					120	24	100
Hylastes ater (Black pine bark beetle)	Zhang (2006)	Sawdust from pine logs	Adult	15	15	24	100
					30	24	100

					60	24	100
					120	24	100
			Larva	15	15	24	100
					30	24	100
					60	24	100
					120	24	100
Semanotus japonicus (Cryptomeria bark borer)	Soma *et al*. (1996)	n/a	Egg	15	19	48	LD50
					40	48	LD95
			Larva	15	2	24	LD50
					5	24	LD95
Callidiellum rufipenne (Small cedar longhorn beetle)	Soma *et al*. (1996)	Under bark of cedar and cypress logs	Immature larva	15	2	24	LD50
					4	24	LD95

		Inside xylem of cedar and cypress logs	Mature larva	15	6	24	LD50
					21	24	LD95
			Pupa	15	3	24	LD50
					8	24	LD95
		Inside xylem of cedar and cypress logs	Adult	15	4	24	LD50
					8	24	LD95
Monochamus alternatus (Japanese pine sawyer)	Soma *et al*. (1996)	n/a	Mature larva	15	4	24	LD50
					8	24	LD95
Cryphalus fulvus (Small pine bark beetle)	Soma *et al*. (1996)	Bark of red pine logs	Egg	15	52	24	LD50
					87	24	LD95
					130	24	100

Ips cembrae (Larch ips)	Soma *et al*. (1996)	n/a	Adult	15	1	24	LD50
					2	24	LD95
Phloeosinus perlatus (Thuja bark beetle)	Soma *et al*. (1996)	Bark of cypress logs	Egg	15	42	24	LD50
					61	24	LD95
			Larva	15	1	24	LD50
					3	24	LD95
Sirahoshizo sp.	Soma *et al*. (1996)	Pine logs	Larva	15	7	24	LD50
					25	24	LD95
Xyleborus pfeili (ambrosia beetle)	Mizobuti *et al*. (1996)	Sawdust	Egg	15	40	48	11.1
					50	48	23.1
			Larva	15	27	24	LD50
					82	24	LD95

		20	48	91.1
		30	48	90.4
		40	48	97.6
		50	48	98.8
Pupa	15	4	24	LD50
		77	24	LD95
		20	48	100
		30	48	100
		40	48	100
		50	48	100
Adult	15	10	24	100
		20	48	100
		30	48	100
		40	48	100

					50	48	100
Xyleborus validus (ambrosia beetle)	Mizobuti *et al*. (1996)	Cedar logs	Adult	15	5	24	100
Xylosandrus germanus (ambrosia beetle)	Mizobuti *et al*. (1996)	Cedar logs	Adult	15	5	24	100
Platypus calamus (ambrosia beetle)	Mizobuti *et al*. (1996)	Cedar logs	Larva	15	15	24	100
			Adult	15	15	24	100
Platypus quercivorus (ambrosia beetle)	Mizobuti *et al*. (1996)	Oak logs	Larva	15	15	24	100
			Adult	15	15	24	100
Anoplophora glabripennis (Asian long horned beetle)	Barak *et al*. 2006	Timber	Larva	4	154	24	Probit 9
				10	121	24	Probit 9
				16	104	24	Probit 9

				21	88	24	Probit 9
Agrilus planipennis (Emerald ash borer)	Barak *et al*. 2010	Ash logs	Egg	21	130	24	91.7
					146	24	95.5
					79	48	98.3
					95	48	100
			Larva (adult emergence from logs measured)	10	144	24	99.9
					112	48	99.9
				16	136	24	100
					104	48	99.9
					144	24	100
					128	48	100
				21	128	24	100

					104	48	100
				24	144	24	100
					128	24	100
				25	128	48	100
				26	104	48	100
Chlorophorus annularis (Bamboo borer)	Yu *et al*. (2010)	Bamboo poles	Larva	16	96	24	100
				22	80	24	100
				23	64	24	100
					80	24	100
					96	24	100
					112	24	100
				26	64	24	100
			Pupa	23	64	24	100
					80	24	100

					96	24	100
					112	24	100
			Adult	23	64	24	100
					80	24	100
					96	24	100
					112	24	100
Bursaphelenchus xylophilus (Pine wood nematode)	Buckley *et al*. (2010)	Unseasoned pine sticks, sawn from logs	Adult	15	92	24	50
					126	24	100
				20	31	24	30
					61	24	90
					71	24	50
					89	24	100
					109	24	100

	25	60	24	100
	30	51	24	100
		60	24	100

2.3 Phosphine

Phosphine is toxic to a broad range of insect and rodent pests, but degrades to harmless phosphoric acid. It was discovered in the late 1700s, and is one of the oldest fumigants in use. It is highly volatile with a boiling point of -87.4 °C and vapour pressure of 4180 kPa at 20 °C and does not contribute to stratospheric ozone depletion. In contrast to methyl bromide, phosphine is a flammable gas and, therefore, requires extra precautions and safety standards to apply. Phosphine gas disperses rapidly across treatment areas and can penetrate dense materials, including wood, with an efficacy comparable to that of methyl bromide (Ren *et al*. 2011; Hall *et al*. 2018). Globally, phosphine serves as the primary fumigant for the disinfestation of stored food products, particularly grains such as wheat, sorghum, barley, and rice, to control insect pest infestations (Nayak *et al*. 2020).

In Australia, phosphine is registered for control of stored product pests but not for the disinfestation of logs. Conversely, export logs from New Zealand to China are currently treated within the hulls of ships with phosphine gas as a phytosanitary treatment to control potential insect pests (Armstrong *et al*. 2014). China has allowed New Zealand this use on an experimental basis since the early 2000s, and reviews and has renewed this decision annually. China does not currently grant any other country a similar allowance for the use of phosphine (Armstrong *et al*. 2014). Officially, however, neither India nor China has approved phosphine as a phytosanitary treatment for imported logs, from any country. Due to its low cost compared with methyl bromide, industry regards adoption of phosphine as economically feasible (Table 1, personal communication R. Brooks, Pacific Forest Products).

The most widely adopted fumigation schedule for phosphine gas includes an exposure at >200 ppm at 15°C for 10 days (i.e., initial dose of 1400 ppm for 120 h followed by a top-up dose of 1050 ppm). Research has demonstrated that this treatment regimen is often effective against stored product insect pests in Africa, Australia, China, and the United States (Armstrong *et al*. 2014). This treatment schedule can be maintained within the hulls of ships, theoretically enabling the disinfestation of commodities in transit, and is the current industry standard for the export of logs from New Zealand to China. This is achieved by applying 2 g/m^3 of aluminium phosphide to each ship hold at departure, followed by a top-up of an additional 1.5 g/m^3 after 5 days (Frontline Biosecurity Ltd and MAF Forest Biosecurity 2004, Armstrong *et al*. 2014).

Despite its initial effectiveness against stored product pests and continued use worldwide as a phytosanitary treatment, many insect pest species have developed resistance to phosphine (Hall *et al*. 2025, Nayak *et al*. 2020). For example, reports from Australia indicate that phosphine fumigations have become increasingly ineffective at controlling stored product pests such as *Tribolium confusum*, *Rhyzopertha dominica*, *Cryptolestes ferrugineus*, and others. Moreover, research studies indicate that the frequency of phosphine resistance in populations of specific pest species of stored-products have increased to over 80% in Australia (Nayak *et al*. 2020). This resistance has hindered international trade between Australia and importers and poses growing challenges for industry. Moreover, many stored grain insect pests, including *T. confusum* are related (i.e., same Family) to forestry pests.

Some studies have shown that the current phosphine treatment schedule for logs in New Zealand is sufficient to control key insect pests, such as *Arhopalus ferus* (burnt pine longhorn), *Prionoplus reticularis* (huhu beetle), *Hylastes ater* (black pine bark beetle), *Hylurgus ligniperda* (bark beetle), and *Sirex noctilio* (Sirex wasp) (Zhang *et al*. 2004; Glassey *et al*. 2005, Frontline Biosecurity Ltd and MAF Forest Biosecurity 2004). Notably, *H. ater*, *H. ligniperda*, and *S. noctilio* are also pests of Australian logs and are considered undesirable exotic pests in China and India. Conversely, studies have demonstrated that the current treatment schedule for phosphine fumigation does not control 100% of pupa or adults of *H. ligniperda* (Esfandi *et al*. 2022; Devitt 2021). A study by Devitt *et al*. (2020) suggests that respiration of logs in-hull of ships creates a hypoxic and hypercapnic atmosphere, thus reducing the efficacy of phosphine against pest species. Moreover, recent incursions of *H. ligniperda* in China have been linked to imports of phosphine-treated logs originating from New Zealand (Lin et al. 2021a, b). Studies have also shown that phosphine lacks efficacy against a broader range of insect, nematode and fungal pest species of logs (Oogita *et al*. 1997; Armstrong *et al*. 2014, Uzunovic *et al*. 2009; Baker *et al*. 2003a). These conflicting results suggest that additional investigation is warranted to determine if the current treatment schedule for phosphine fumigation of logs in New Zealand is effective against pests in Australia. A similar data set against the diversity of pests produced for ethanedinitrile is likely to be required to support any acceptance of phosphine as a phytosanitary treatment for logs by Australia’s trading partners.

A comprehensive review by Hall *et al*. (2025), of more than 40 scientific studies, addressed the efficacy and limitations of phosphine fumigation as a phytosanitary treatment of wood products. The authors concluded that there is insufficient evidence supporting phosphine as a broad-spectrum quarantine treatment for wood products. The review showed that phosphine was effective against some forest insects but often failed to meet quarantine treatment standards and was ineffective against nematodes and fungi. The authors recommended that future research should provide scientific evidence of the effectiveness of phosphine against specific pest or pest groups under conditions that are representative of industry requirements.

2.4 Methyl iodide

Methyl iodide and methyl bromide have similar chemical structures (both halogenated hydrocarbons), physical characteristics, vapor pressures (methyl iodide 55 kPa at 20°C) and mechanisms of toxicology against pests (Ntow and Ajwa 2010, Mattner 2012). Unlike methyl bromide, however, methyl iodide breaks down by photolysis before it can reach the stratosphere and has negligible ozone-depleting potential (Mattner 2012). Sorption for methyl iodide into wood products appears to be greater than that of methyl bromide (although they have not been compared directly), based on the increased density of the compound (Soma *et al*. 2005 & 2006). There is no current information in the literature on rates of desorption from logs after fumigation (Klementz and Brash 2010). This information is vital to understand withholding periods for methyl iodide following treatments, especially when considering fumigation in confined spaces such as the hulls of ships. Methyl iodide is registered for treatment of soils for strawberry runner production in Australia, but not for the disinfestation of logs.

As with other fumigants, the efficacy of methyl iodide against insect pests of wood products is variable and dependant on the target species, life stage, temperature during application and application rate (Table 5). However, total mortality was consistently achieved across all species and life stages of insect pests (14) at rates equal to or above 60 g/m³, irrespective of other parameters (Table 5). Methyl iodide was also effective at controlling nematodes and fungal pathogens within wood products, though only three species appear to have been assessed (Table 5). Most research on methyl iodide occurred in Japan, where it is currently registered for QPS use to control insect pests in timber (MBTOC 2010). In Japan, application rates of 25 – 50 g/m³ are registered for commodity treatments (Izutsuya, http://www.izutsuya-chem.co.jp/). Compared with EDN, there is limited efficacy data available relating to the control of key pest species of logs in Australia (e.g., Sirex wood wasps) with methyl iodide (Tables 3 & 5). This data would be required to register methyl iodide in Australia for log treatments and to support its acceptance by India and China as a phytosanitary measure. Further, the cost of treatment and economic viability of methyl iodide fumigation of logs is highly dependant on the rate/s required to achieve total control (100% mortality) of key insect pest species (Table 1).

Table 5. List of studies that assessed the effectiveness of methyl iodide fumigation for control of pests in wood products. The species name and life stage (if applicable), the commodity, the fumigation parameters (temperature, rate, exposure time), and the proportion of pest mortality are reported. Symbols representing missing information (**-**) are included.

Pest species	Source	Commodity	Life stage	Temperature (ºC)	Rate (g/m³)	Exposure time (h)	Mortality (%)
Arhoalus rusticus (Longhorn beetle)	Abe *et al*. (2012)	Lumber (red pine)	Adult	10	84	24	100
				15	60	24	100
				20	64	24	100
				25	48	24	100
	MBTOC (2010)	_	_	10	84	-	100
				15	60	-	100
				20	64	-	100
				25	48	-	100
Bursaphelenchus xylophilus (Pine wood nematode)	Abe *et al*. (2012)	Lumber (red pine)	Adult	25	36	24	76
	Soma *et al*. (2005)	Lumber (red pine)	Adult	10	40	24	99.9
				10	50	24	99.9
				10	60	24	100

				15	20	24	99.9
				15	30	24	99.9
				15	40	24	100
				15	50	24	100
				20	30	24	99.9
				20	40	24	100
				25	10	24	99.9
				25	20	24	99.1
				25	30	24	100
Callidiellum rufipenne (Small cedar longhorn beetle)	Naito *et al*. (2003)	Paper	Egg	15	5	24	100
					10	24	100
					15	24	100
		Bark (cedar)	Larva	15	10	24	100
					15	24	100
					30	24	100
					50	24	100
		Logs (cedar)	Larva	15	30	24	96.8

					50	24	95.5
	Soma et al. (2007)	Logs (cedar)	Adult	8-10.6	60	24	100
			Adult	8-10.6	120	24	100
Cerambycidae (Gen. *et* sp.) (Longhorn bettle)	Soma *et al*. (2007)	Logs (Malaysian logs)	Larva	8-10.6	60	24	100
				8-10.6	120	24	100
Ceratocystis fagacearum (wood-decaying fungi)	Tubajika & Barak (2011)	Wood blocks (birch, red pine, maple, poplar)	n/a	21±2	160	24	94.5
					160	48	99.2
					160	72	100
					240	24	99.2
					240	48	100
					240	72	100
Cryphalus fulvus (Small pine bark beetle)	Naito *et al*. (2003)	Bark (red pine)	Egg	15	10	24	100
					30	24	100
					50	24	100
			Larva	15	10	24	100

					15	24	100
					30	24	100
					50	24	100
			Pupa	15	10	24	92.3
					15	24	100
					30	24	100
					50	24	100
			Adult	15	10	24	100
					15	24	100
					30	24	100
					50	24	100
	Soma *et al*. (2007)	Logs (red pine)	Egg	8-10.6	60	24	100
			Larva	8-10.6	60	24	100
			Pupa	8-10.6	60	24	100
			Adult	8-10.6	60	24	100
			Larva	8-10.6	120	24	100
			Adult	8-10.6	120	24	100
Cryptoteryes brevis (West	Ohr *et al*. (1998)	Paper	Adult	20	1.8	27	15

Indian drywood termite)							
					2	27	15
					2.4	27	55
					3	27	100
					3.6	27	100
					4	27	100
					8	27	100
					16	27	100
Ips cembrae (Larch Ips)	Naito *et al*. (2003)	Bark (lark and red pine)	Larva	15	30	24	100
			Pupa	15	30	24	100
			Adult	15	30	24	100
Monochamus alternatus (Japanese pine sawyer)	Naito *et al*. (2003)	Bark (red pine)	Egg	15	30	24	100
		Logs (red pine)	Larva	15	15	24	63.3
					30	24	85.7
					50	24	100
			Pupa	15	15	24	62.5

					30	24	80
					50	24	100
	Abe *et al*. (2012)	Lumber (red pine)	Adult	10	84	24	100
				15	60	24	100
				20	64	24	100
				25	48	24	100
	Soma *et al*. (2007)	Logs (red pine)	Larva	8-10.6	60	24	100
			Larva	8-10.6	120	24	100
	MBTOC (2010)	_	_	10	84	-	100
				15	60	-	100
				20	64	-	100
				25	48	-	100
Pissodes Nitidus (Pine weevil)	Naito *et al*. (2003)	Bark (red pine)	Egg	15	5	24	99.4
					10	24	100
					15	24	100
					50	24	100
			Larva	15	10	24	99.3
					15	24	100

					30	24	100
					50	24	100
			Pupa	15	10	24	99.1
					15	24	98.8
					30	24	100
Platypus sp. (Pine borer)	Soma *et al*. (2007)	Logs (Malaysian logs)	Egg	8-10.6	60	24	100
			Larva	8-10.6	60	24	100
			Pupa	8-10.6	60	24	100
			Adult	8-10.6	60	24	100
			Larva	8-10.6	120	24	100
			Pupa	8-10.6	120	24	100
			Adult	8-10.6	120	24	100
Semanotus japonicus (Cryptomeria bark borer)	Naito *et al*. (2003)	Paper	Egg	15	5	24	99.6
					10	24	100
					15	24	100
					30	24	100

Shirahoshizo Rufescens (weevil)	Naito *et al*. (2003)	Bark (black pine and red pine)	Larva	15	10	24	85.7
					15	24	88.6
					30	24	92.9
					50	24	100
Xyleborus pfeili (ambrosia beetle)	Naito *et al*. (2003)	Artificial diet	Egg	15	10	24	100
					15	24	100
					50	24	100
			Larva	15	10	24	100
					15	24	100
					30	24	100
					50	24	100
			Pupa	15	10	24	100
					15	24	100
					30	24	100
					50	24	100
			Adult	15	10	24	100

					15	24	100
					30	24	100
					50	24	100
Xyleborus perforans (Island pinhole borer)	Soma *et al*. (2007)	Logs	Larva	8-10.6	60	24	100
			Pupa	8-10.6	60	24	100
			Adult	8-10.6	60	24	100
			Egg	8-10.6	120	24	100
			Larva	8-10.6	120	24	100
			Pupa	8-10.6	120	24	100
			Adult	8-10.6	120	24	100
Xyleborus sp. (bark beetle)	Soma *et al*. (2007)	Logs (Malaysian logs)	Egg	8-10.6	60	24	100
			Larva	8-10.6	60	24	100
			Pupa	8-10.6	60	24	100
			Adult	8-10.6	60	24	100
			Egg	8-10.6	120	24	100
			Larva	8-10.6	120	24	100
			Pupa	8-10.6	120	24	100

			Adult	8-10.6	120	24	100
Xylosandrus germanus (ambrosia beetle)	Naito *et al*. (2003)	Logs (cedar and acer)	Egg	15	50	24	100
			Larva	15	30	24	100
					50	24	100
			Pupa	15	50	24	100
			Adult	15	30	24	100
					50	24	100

2.5 Other chemical treatments

Several other notable chemical treatments have been considered for the disinfestation of logs in the past (Armstrong *et al*. 2014). However, most of these treatments are not registered for use in Australia, currently lack sufficient efficacy data for registration, or have additional drawbacks thought to hinder adoption by industry (Table 6). For these reasons, many of these treatments have been de-prioritised as potential alternatives to methyl bromide for treatment of logs.

Table 6. Summary of chemical phytosanitary treatments that have been commonly disregarded as viable alternatives to methyl bromide for the disinfestation of logs. Efficacy data is lacking for all treatments, regarding control of pest species of logs in Australia.

Treatment	Registration in Australia for treatment of logs and acceptance by trading partners	Examples of efficacy against forestry pest species	Risks and barriers to adoption
Ethyl formate	Not registered. Not accepted by trading partners.	n/a	Lacks the ability to effectively penetrate logs. Flammable.
Ethylene oxide/ Propylene oxide	Not registered. Accepted by Tonga.	n/a	Must be applied in a confined space whereby all oxygen can be removed from the treatment area. Not practically or economically scalable to disinfest logs. Flammable.
Chloropicrin	Not registered. Not accepted by trading partners.	Schmidt & Christopherson 1997; Highley 1991; Highley & Eslyn 1989a, b; Hutchinson *et al*. 2000.	Difficult to apply due to low volatility. Lacks the ability to effectively penetrate logs.
Dimethyl disulphide	Not registered. Not accepted by trading partners.	n/a	Flammable. Difficult to apply due to low volatility.

			Strong displeasing (obnoxious) and persisting odour.
Isothiocyanates, including mixtures with sulfuryl fluoride	Not registered. Not accepted by trading partners.	Soma *et al*. 2004; Abe *et al*. 2004	Flammable. Strong displeasing odour. Difficult to apply due to low volatility.
Carbonyl sulphide	Not registered. Not accepted by trading partners.	Gan *et al*. 2005 ; Ren *et al*. 1997.	Flammable. Strong displeasing odour.
Hydrogen cyanide	Not registered. Not accepted by trading partners.	Stejskal *et al*. 2014; Stejskal *et al*. 2012; Bond 1984; Parkin and Busvie 1937; Bletchly 1953	Lacks the ability to effectively penetrate logs. Flammable.

2.6 Heat treatment

Heat treatment is recognized by India and China as an acceptable phytosanitary measure for the importation of Australian logs (Table 2). The Australian Department of Agriculture, Fisheries and Forestry also endorses heat treatments for various commodities, and provide standard guidelines for its use, which are accessible online (https://www.agriculture.gov.au/biosecurity-trade/import/arrival/treatments/treatments-fumigants#heat-treatment_2). Notably, due to evaporation of water content within heat treated logs, shipments may incur reduce fuel costs compared with standard fumigation treatments, due to weight loss. Research indicates that temperatures exceeding 50°C effectively control a range of pest species across different commodities (Hansen *et al*. 2011). Studies targeting pest species of logs such as *Hylurgus ligniperda* and *Arhopalus ferus* have demonstrated that heat treatment is highly efficacious (Myers *et al*. 2009, Pawson *et al*. 2019). Three primary methods have been investigated for heating logs to high temperatures to control pests: dry heat, joule heating, and microwave technologies.

2.6.1 Dry heat

Dry heating is the simplest method, involving the placement of logs in a confined space, such as a shipping container, to minimize heat loss. The logs are gradually heated via conduction using electric heaters. Depending on environmental conditions, achieving the desired core temperature in the logs (e.g., 56 °C) may take over five days (personal communication Precision Pest Control). Although commercial dry heat applications are available for small-scale industry use, the treatment's cost is considerably more expensive than the use of fumigants (Table 1).

2.6.2 Joule heating

In contrast to dry heat, joule heating can achieve the necessary temperatures for log disinfestation within minutes, opposed to days (Heffernan 2013, Pawson *et al*. 2019). This method involves passing an electrical current through individual logs, with electrodes placed at both ends and alternating current (AC) excitation applied (Pawson *et al*. 2019). Heffernan (2013) proposed a conveyor system capable of processing one log per minute using joule heating. However, despite its efficacy against pest species, as demonstrated by Pawson *et al*. (2019), the high initial investment costs and significant operational adjustments required for large-scale treatment render joule heating more expensive than fumigants at present.

2.6.3 Microwave technologies

Microwave systems have been used to disinfest commodities, including soils, grain, and hay (Brodie 2007, Brodie *et al*. 2015). Microwaves are efficient at heating logs internally, as they can penetrate wood with minimal resistance (Tang et al. 2007). Moreover, studies have shown that microwave heating can control termites in timber (Lewis *et al*. 2000, Yanagawa *et al*. 2020). However, no study appears to have tested microwave heating at the scale necessary for the disinfestation of Australian logs for export. Cost models for microwave treatment of logs suggest expenses could range from AU$22 to AU$69 per cubic meter (Torgovnikov and Vinden 2010). Based on these cost estimates microwave treatment of logs is currently considered more expensive than fumigants (McFarlane *et al*. 2023)

2.7 Removal of bark

China accepts debarking as an alternative treatment to methyl bromide fumigation for the importation of logs from Australia (Manual of Importing Country Requirements https://micor.agriculture.gov.au/Plants/Pages/China_CN/All4.aspx). In theory, debarking assists in the removal of forestry pests that live in or under the bark layer (e.g., bark beetles). However, pest species that penetrate through the bark layer and reside within the sapwood and/or heartwood of logs (e.g., Sirex wood wasps) are unlikely to be controlled by the treatment. India does not accept debarking as a treatment of Australian logs for import. Debarking is not cost effective for industry, in comparison with methyl bromide fumigation, due to operational expenses and management of waste materials (i.e., bark) (Table 1).

2.8 Immersion in water

There is little efficacy data available in the scientific literature on the control of pest species of logs with water immersion (Knuth 1960). Studies claim that logs submerged in water are protected from drying defects and from insect and fungi attacks. Pond storage appears to have been common in the early 1900's, but has more or less ceased due to its negative impact on water and wood quality (Olsson 2005).

China accepts immersion of logs in water for 90 days as an alternative phytosanitary treatment to methyl bromide for log imports from Australia. Australia does not currently have a facility to conduct log immersion in water at the scale required for export. The construction and operational costs associated with this treatment are not considered economically viable by industry, compared with methyl bromide fumigation (Table 1). Further, India does not accept immersion in water as a phytosanitary treatment of Australian logs for import.

2.9 Gamma irradiation

Gamma irradiation is not reliant on humidity, temperature or pressure. Organic substances, including bacteria, fungi and insects, exposed to gamma rays experience a disruption to their organic processes as their DNA is broken down by the treatment. Irradiation with gamma rays is used commercially in Australia to kill insect, bacterial and fungal pests on various commodities, including fruits, vegetables and meats. Studies have shown that gamma irradiation can be efficacious against insect, fungi and nematode pests in wood products (Kalawate and Mehetre 2015, Eicholz *et al*. 1991 and Yoshida *et al*. 1975). However, the irradiation doses required to kill nematodes (6000 – 8000 Gy) and ambrosia beetles (730 – 1300 Gy) far exceed commercial applications of gamma rays to disinfest horticultural and meat products in Australia (~300 Gy) (Eicholz *et al*. 1991, Yoshida *et al*. 1975). Yoshida *et al*. (1975) showed that far lower doses of gamma radiation, ranging from 20-40 Gy, were required to sterilise ambrosia beetles, across all life stages. Further, a study by Haandel *et al*. (2017) showed that two pest species of pine logs in New Zealand, *Hylurgus ligniperda* and *Arhopalus ferus* were both susceptible sterility to gamma radiation doses <150 Gy. Sterilisation of insect pests of logs is not recognised as an appropriate control measure by Australia, China or India. Additional studies would be required to evaluate the efficacy of gamma radiation against key pest species of logs and to approve sterility as a control measure. Further, irrespective of its efficacy against pest species of logs, the current economic costs associated with the treatment are considerably higher than that of standard fumigation practices.

2.10 Controlled and modified atmospheres

Controlled and modified atmospheres are techniques used to manage the gas composition surrounding commodities, such as logs, to create lethal conditions for pest species. These treatments typically reduce the concentration of oxygen while increasing levels of carbon dioxide or nitrogen in the target area. The resulting low-oxygen environment inhibits the respiratory activity of living organisms, including pest insects, leading to their death or reduced activity (Yahia 2010; Schroeder and Eidmann 1986).

A study by Dentener *et al*. (1997) demonstrated that *Prionoplus reticularis* larvae, a significant pest of logs in New Zealand, can be killed in modified atmospheres after 10 days of exposure to over 99% carbon dioxide or nitrogen levels. However, mortality rates were highly variable (0-88%) and dependent on the size of the larvae. The efficacy of the treatment improved significantly (>99%) when combined with simultaneous heat treatment, maintained at 40°C.

Currently, controlled and modified atmosphere treatments are not accepted as phytosanitary treatments for logs by India or China. To gain acceptance from trading partners, significantly more data is needed to evaluate the treatment's efficacy against key pests of logs in Australia. Additionally, these treatments are considerably more expensive to operate than standard fumigation practices, and the initial investment required to scale up the treatment for industry use is substantial (Armstrong *et al*. 2014).

2.11 Recapture of methyl bromide

Recapture systems utilize activated charcoal filters and vacuum technology to filter the atmosphere in treated areas after fumigation, immediately prior to venting. These systems, available commercially in Australia and abroad, effectively recapture methyl bromide following treatment (e.g., Nordiko Quarantine Systems https://nordiko.com.au/wp/). The captured methyl bromide is retained on the activated carbon, preventing it from entering the atmosphere and contributing to stratospheric ozone depletion. Additionally, the recapture systems help reduce operator exposure to fumigant gases during the aeration period, potentially allowing for smaller buffer zones during venting. Implementing methyl bromide recapture entails an additional cost to standard fumigation practices. However, despite the increased costs, methyl bromide recapture could serve as an interim solution that the industry might adopt to gradually reduce the impact of methyl bromide on the environment, especially if mandated by government or international regulations. Research by McFarlane *et al*. (2023) showed that recapture technologies can also be used very effectively for methyl iodide.

3.0 Conclusions

There is growing political pressure for Australia to reduce its use of methyl bromide, especially since the European Union stopped using the fumigant and other countries (e.g., New Zealand) ban emissions of the compound to the atmosphere. Australia urgently needs alternatives to methyl bromide that are effective against pests, sustainable for the environment, readily accepted by trading partners, easy to apply, safe for users when handled correctly, are cost effective, and do not adversely affect commodities.

This review has prioritised a number of alternatives to methyl bromide for possible adoption for export logs in Australia based on technical data, the status of registration in Australia, the acceptance of the treatment by key trading partners, and other risks and costs. These alternatives include fumigation with either ethanedinitrile, phosphine, methyl iodide or sulfuryl fluoride; heat treatments; removal of bark; immersion in water; gamma irradiation; controlled and modified atmospheres; and methyl bromide recapture. Each of these alternatives has gaps in RD&E, registration and approval that must be addressed before the log industry can fully adopt them.

For example, ethanedinitrile requires improved communication between the chemical registrant (Draslovka), fumigators, and exporters to assess treatment costs. Conversely, while methyl iodide is highly effective against log pests, it is still in the early stages of development. It requires further research on its effects against a broader range of pests and to determine effective application rates and conditions. It is unlikely that a single solution will replace methyl bromide use in Australia for log disinfestation. Future disinfestation systems for logs will likely depend on a combination of multiple chemistries and management practices to effectively control pests prior to export.

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