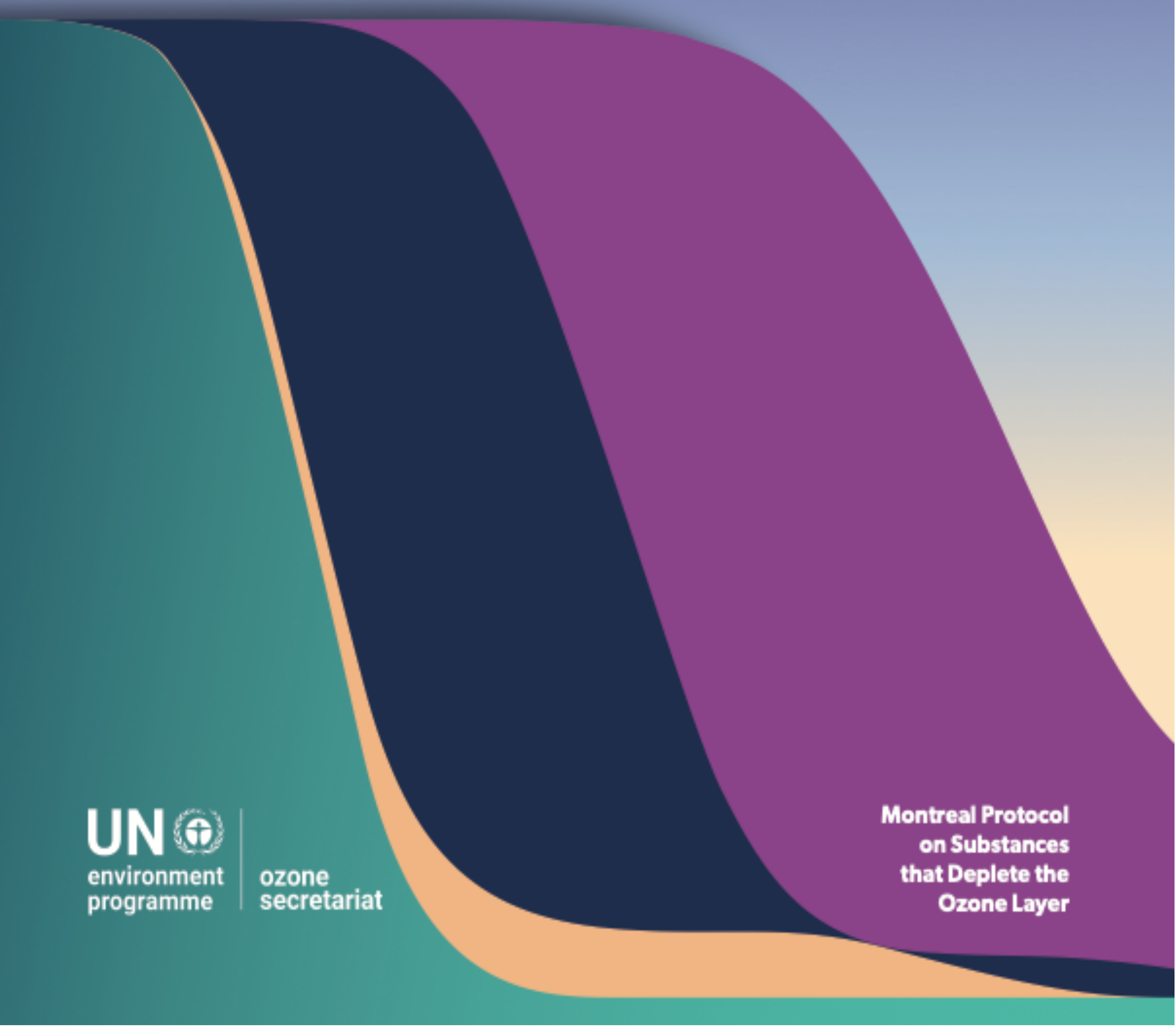
Methyl Bromide Technical Options Committee

2022 Assessment Report



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Montreal Protocol on Substances that Deplete the Ozone Layer

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United Nations Environment Programme (UNEP)
2022 Report of the Methyl Bromide Technical Options Committee

2022 Assessment

The text of this report is composed mainly in Times New Roman.

Composition of the Report:	Methyl Bromide Technical Options Committee
Coordination:	Ian Porter, Marta Pizano, MBTOC Co-Chairs.
Final editing and layout:	Marta Pizano, Ian Porter, MBTOC co-chairs
Reproduction:	UNEP/ Ozone Secretariat, Nairobi
Date:	January 2023

Under certain conditions, printed copies of this report are available from:

United Nations Environment Programme
Ozone Secretariat
P.O. Box 30552
Nairobi, Kenya

This document is also available in portable document format from:
http://ozone.unep.org/science/assessment/teap

ISBN: 978-9914-733-95-2

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Acknowledgments: MBTOC acknowledges support from Dr Paul Fraser and Nada Derek for Chapter 4 of this report in assisting with preparation of some text, figures and review of information.

UNEP
2022 REPORT OF THE
METHYL BROMIDE
TECHNICAL OPTIONS COMMITTEE

2022 ASSESSMENT

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Glossary of Acronyms

1,3-D	1,3-Dichloropropene
A5	Article 5
AITC	Allyl isothiocyanate
ASD	Anaerobic soil disinfestation
CUE	Critical Use Exemption
CUN	Critical Use Nomination
DOI	Disclosure of Interest
EDN	Ethanedinitrile
EU	European Union
EPA	Environmental Protection Agency
EPPO	European Plant Protection Organisation
IPM	Integrated Pest Management
IPPC	International Plant Protection Convention
ISPM	International Standard for Phytosanitary Measure
LPBF	Low Permeability Barrier Film (including VIF films)
MB	Methyl bromide
MBTOC	Methyl Bromide Technical Options Committee
MI	Methyl iodide
MITC	Methyl isothiocyanate
MOP	Meeting of the Parties
MS	Metham sodium
Non-A5	Non Article 5
NPPO	National Plant Protection Organisation
OEWG	Open Ended Working Group
Pic	Chloropicrin
QPS	Quarantine and Pre-shipment
SDG	Sustainable Development Goals
SF	Sulfuryl fluoride
TEAP	Technology and Economics Assessment Panel
TIF	Totally Impermeable Film
USA	United States of America
VIF	Virtually Impermeable Film
VOC	Volatile Organic Compound
WMO	World Meteorological Organisation

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1. Executive Summary

1.1. Concise Summary

Phaseout of controlled, non-exempted (i.e. non-Quarantine and Preshipment) uses of methyl bromide (MB) is virtually complete. Parties report that greater than 99.8% of the baseline consumption of 66,428 tonnes for these controlled non-QPS uses has been phased out by 1 Jan 2023. There are only two remaining uses which are still applying for CUNs in 2022 in non- A5 parties for preplant soil fumigation in strawberry nursery industries and one reported use for structural fumigation of houses in A5 countries. In 2021, reported MB consumption for controlled uses was around 40 tonnes. All other non-exempt uses of MB have been replaced by other processes. A relatively small, but significant amount of stocks may be being used for some other unreported controlled uses of MB, possibly amounting to around 1,000 tonnes.

The phasing out of MB under the control measures of the Montreal Protocol (Annex E) has led to over 30% of the present decline in ozone degrading chemical concentration in the atmosphere (i.e. Effective Equivalent Stratospheric Chlorine- EESC). This is the single largest contribution to improvement of the ozone layer from any chemical at this time.

In 2021, 100% of reported MB production was for QPS purposes, and production for controlled uses was zero. Since 2018, no Party has reported production of MB for controlled uses (non-QPS). However, MBTOC notes once again that MB is still offered on the internet for any use, including preplant soil fumigation and treatment of stored products.

Annual consumption of MB for QPS purposes, an exempted use, has remained relatively constant over more than 20 years, at around 10,000 tonnes. Seventeen countries use about 94% of the reported QPS consumption and only 55 of 198 parties report use of MB for QPS. Data also shows that in 2021 A5 Parties accounted for 57% of global MB consumption for QPS purposes (5,976 tonnes), down from 67% in 2017; non-A5 Party consumption, at 4,489 tonnes was 43%, up from 31% in 2017. MBTOC reinforces that alternatives are available for most preshipment uses and if adopted could result in replacing 30-40% (i.e. 3,000-4,000 tonnes) of the total QPS MB.

Elimination of emissions from QPS use is the single largest short-term gain that could be made to further reduction of EESC and improvement in the ozone layer. Complete elimination of emissions from QPS use of MB, could result in a further significant (i.e. ~10%) and rapid reduction to the present EESC. This is one of the very few measures available to Parties that would result in this magnitude of rapid reduction. Technical alternatives to both Q and PS purposes are becoming increasing available, with new chemicals such as ethane dinitrile and hydrogen cyanide showing good efficacy against pests. Emissions can also be managed through use of recapture technologies.

1.2. Mandate and report structure

Under Decision XXXI/2 taken at the Thirty-First Meeting of the Parties to the Protocol in 2019, the Parties requested the Assessment Panels to update their 2018 reports in 2022 and submit them to the Secretariat by 31 December 2022 for consideration by the Open-ended Working Group and by the Thirty Fifth Meeting of the Parties to the Montreal Protocol, in 2022.

The MBTOC 2022 Assessment reports on advances since 2018 to replace MB), now exclusively used under Critical Use by both A5 and non-Article 5 Parties. It also reports on QPS uses, which are presently exempt from controls under the Montreal Protocol. It covers technically and economically feasible alternatives for non-QPS and QPS uses of MB and gives actual examples of their successful commercial adoption around the world. It shows trends in MB production and consumption in both Article 5 and non-Article 5 Parties, estimated levels of emissions of MB to the atmosphere, and strategies to reduce those emissions.

1.3. The Methyl Bromide Technical Options Committee (MBTOC)

As of December 2022, MBTOC has 16 members; nine (56%) from non-Article 5 and seven (44%) from Article 5 Parties. These members come from seven Article 5 and eight non- Article 5 countries.

1.4. Methyl bromide control measures

Methyl bromide was listed under the Montreal Protocol as a controlled ozone depleting substance in 1992. Control schedules leading to phase-out were agreed in 1995 and 1997. There are a number of concerns apart from ozone depletion that also led countries to impose severe restrictions on MB use including toxicity to humans and associated operator safety and public health, and detrimental effects on soil biodiversity. In some countries, pollution of surface and ground water by MB and its derived bromide ion are also of concern.

The control measures, agreed by the Parties at their ninth Meeting in Montreal in September 1997, were for phase out of MB by 1 January 2005 in non-Article 5 countries. For Parties operating under Article 5 of the Protocol (developing countries) the control measures were for a 20% cut in production and consumption, based on the average in 1995-98, from 1 January 2005 and phase out by 1 January 2015. Since 2003, nine non-Article 5 Parties have submitted nearly 150 applications for 18,700 tonnes for 'Critical Uses' after 2005 for non-QPS purposes under Article 2H of the Montreal Protocol. By 2022 the number had declined to two applications for approximately 20 tonnes for use in 2023 and 2024.

Use of MB under the 'Critical Use' provisions became available to 'Article 5 countries in 2015 and initially four countries applied for 590 tonnes of MB after 2014. In 2022, only one party requested 20 tonnes of MB under the CUE provisions for use in 2023.

Although QPS uses must be officially reported under Article 7 of the Protocol they continue to be exempt from controls under Article 2H.

Recently, during its 18th meeting, the Chemical Review Committee (CRC) of the Rotterdam Convention held in September 2022 recommended that MB be listed under Annex III of the Rotterdam Convention, which includes pesticides and industrial chemicals that have been banned or severely restricted for health or environmental reasons. If the Conference of the Parties to this convention accepts this recommendation, then MB will be subjected to the Prior Informed Consent procedure enabling its 165 parties to share information and responsibility and take decisions on potential future imports. MBTOC will continue to watch this issue closely and assess its impacts on MB use and availability.

1.5. Production and consumption trends (controlled uses)

At the time of writing this report, all Parties had submitted data to the Ozone Secretariat for controlled uses in 2021 except Israel. Although a few cases of data gaps remain from the early years, reported data has become much more complete. All tonnages are given in metric tonnes in this report.

In 2021, global *production* for the MB uses controlled under the Protocol was reported at a negative value of -38.66 tonnes, indicating that quantities exported or destroyed exceeded production for that year and that such quantities were taken from stockpiles. Production was thus considered zero compared to the 1991 reported production of 66,430 tonnes. Since 2018, no party has reported production of MB for controlled uses.

Global *consumption* of MB for controlled uses was reported to be 64,420 tonnes in 1991 and remained above 60,000 tonnes until 1998. By 2013, global consumption was estimated at about 2,953 tonnes in 2013 and fell to 245 tonnes in 2017. In 2021 reported consumption fell to negative values, implying that quantities exported exceeded consumption for that year. Consumption for controlled uses was around 40 tonnnes, for CUNs.

The official aggregate baseline for non-A5 countries was 56,083 tonnes in 1991. In 2005 (the first year of critical use provisions), non-A5 consumption had been reduced to 11,470 tonnes, representing 21% of the baseline. Many A5 parties achieved complete phase-out of MB before their 2015 deadline.

In 2021, reported MB consumption for controlled uses was around 40 tonnes (under the critical use exemption), although stocks substantially higher than this may be used in some sectors in various countries. Total stocks are unknown, as only parties requesting CUNs are required to report them. After nearly 20 years of applications for critical uses, the amount of methyl bromide requested has fallen from 18,700 tonnes for 2005 to 40 tonnes submitted for either 2023 or 2024. Non-A5 parties requested CUEs from 2003 and in 2022 only two – Australia and Canada - remain (over 99% of the controlled baseline has been replaced). Only four A-5 parties requested CUNs since 2014, and currently only South Africa remains with a CUE for 2023.

1.6. Alternatives to methyl bromide

MBTOC assumes that an alternative (Refer Decision IX/6 1(a)(ii)) demonstrated in one region of the world would be technically applicable in another unless there were obvious constraints to the contrary e.g., a very different climate or pest complex. Additionally, it is recognised that regulatory requirements, or other very specific constraints or circumstances may make an alternative available in one country but unavailable in another specific country or region. When evaluating CUNs, MBTOC accounts for the specific circumstances of each Party.

Since controls were implemented on MB use in 1992, Parties have been able to identify alternatives for over 99% uses of the baseline consumption. Only 40 tonnes of the original 62,000 tonnes of MB used in 1994 by non-A5 and A5 Parties for controlled reportedly remained in 2021, although there are some uses not reported as an unknown level of stocks of methyl bromide are used. MBTOC considers these stocks may be around 1200 tonnes. The rest of the uses have taken up a wide range of non-chemical and chemical alternatives or developed new production sytsems or technologies which do not require MB fumigation. Of the remaining uses, MBTOC considers alternatives are available, but these may require time for adaptation and adoption.

1.6.1. Alternatives for soil treatments

The reduction in consumption of MB for soil fumigation has been the major contributor to the overall reduction in global consumption of MB for controlled uses with amounts used in 2022 falling 99.9% from about 57,400 tonnes in 1992 to about 20 tonnes, in non-A5 Parties. Substantial stocks of up to 1200 tonnes, MB may still be used in some A5 countries although presently these are not required to be reported.

MB is presently used in non-Article 5 countries for strawberry runner production only. Some preplant soil uses, a portion of which was previously considered under the CUN process, are classified as QPS in one country under national legislation outside of the Montreal Protocol (e.g. forest nurseries, strawberry runners). Since 2018, A5 Parties submitted CUNs for strawberry fruit and runners, ginger and tomatoes. In 2022, no CUN was requested for any A5 soil use of MB.

Over the years, MBTOC has identified a range of key chemical and non chemical alternatives that perform consistently across most regions and sectors. Chemical fumigants (e.g. Metham sodium, dazomet, 1,3 D alone or combined with cholopicrin (Pic,) dimethyl disulfide (DMDS) and others) are widely used around the world and have successfully replaced MB. The registration of methyl iodide has just been granted for one party to use in the strawberry runner industry. A wide range of non-chemical alternatives to MB continue to be trialled around the world including disease-resistant cultivars and grafting desirable varieties onto resistant rootstocks; soil-less culture; anaerobic soil disinfestation; biofumigation and organic amendments; solarisation and biosolarisation; trap cropping; hot water; biological control; and microwaves. A combination of treatments within an IPM program continues to be reported as the most effective approach.

Since 2003, quantities of MB requested for critical use (120 critical use nominations from 10 non-A5 Parties plus the European Union) have fallen from 18,700 t for use in 2005 to 35 t for 2023 use (four CUNs from 3 Parties, two A5 and two non-A5).

This chapter of the 2022 Assessment report focuses on leading economically and technically feasible chemical and non-chemical alternatives for pre-plant soil fumigation adopted in the past by sectors in countries which previously used MB, particularly under the CUE process. It also focuses on alternatives for the remaining MB uses in the soil sector: strawberry runner production in Australia and Canada. In the past, many, strawberry runner industries around the world relied on MB soil fumigation to produce fruit and disease-free strawberry transplants, but most of them have phased-out MB and successfully implemented alternatives.

1.6.2. Alternatives for treatment structures and durable commodities (non-QPS)

In 2022, only one remaining use for 20 t was submitted as a CUN and granted a CUE for structures by the Republic of South Africa. This CUN is the last sector to nominate from A5 parties after only a small number of nominations received from A5 parties after the scheduled phaseout in 2015. At the time of the Copenhagen Amendment (1992), this sector is estimated to have consumed an estimated 6,500 tonnes per year, with much of the reduction since attributable directly to the application of the Montreal Protocol measures.

In this sector and in those countries where MB has been phased out, mainly phosphine and sulfuryl fluoride have taken its place with phosphine mainly adopted for disinfestation of durable products and sulfuryl fluoride mostly for disinfestation of empty structures. In some countries, ethyl formate, hydrogen cyanide and propylene oxide have also been registered and are in use for certain fields of application. The recent registration of ethanedinitrile (EDN) has provided another useful alternative for many products but particularly wood and wooden product exports, which is the largest use of MB for quarantine (est. approx. 4,500 tonnes). The MB phase-out has in general been associated with changes in application technology, logistics and the use of additional IPM measures. There has been some adoption of not-in-kind alternatives (e.g. heat, cold, controlled atmospheres, contact pesticides, biological control). Adoption of particular alternatives has been situation and commodity dependent.

There are continued efforts to improve and register existing alternatives, including fumigants falling into disuse and to develop and register new or more environmentally friendly non-MB approaches. These include systems to avoid pressures to return to MB-dependance.

Several alternatives are under threat and may require replacement or further adaptation within the next few years, at least on a local basis. There is increasing reliance on phosphine treatment for protection of many postharvest durable products in store (e.g. cereal grains, pulses, cocoa beans). However, resistance to phosphine in several pest species has developed, to levels where phosphine is uneconomic due to the very high dosages necessary to control resistant strains. Sulfuryl fluoride fumigation, a potential alternative for the control of insect pests in infested empty structures (warehouses, mills, food and feed factories, wooden structures in houses), has a high GWP that may change its widespread acceptability for use as an alternative to both phosphine and MB. Sulfuryl fluoride is also used for disinfestation of some selected durable products, but these applications are under revision due to the risk of exceeding the maximum residue limits for fluoride. The risk of loosing this fumigant for pest control in structures poses difficult challenges for the MB phase out programs over the recent decade, in particular the disinfestation of large mills and food factories which would remain without feasible pest control measures. Regulatory issues also impact treatment of foodstuffs. Chemical alternatives (and MB itself) are under increasing regulation with potential to making their use infeasible in particular situations.

1.7. Alternatives to methyl bromide for Quarantine and Pre-shipment (QPS) applications (exempted uses)

Article 2H exempts MB used for QPS treatments. MB fumigation is often the preferred treatment for certain types of perishable and durable commodities in trade worldwide, as it has a well-established, successful reputation amongst regulatory authorities to prevent the spread of quarantine pests.

Parties to the Montreal Protocol are nevertheless encouraged to minimize and replace MB for QPS whenever possible, ensuring, among others, that their official lists of quarantine pests are regularly updated and that MB is applied in the most efficient way possible (e.g. observing appropriate dosages, avoiding duplicate treatments, ensuring gas-tightness of fumigation chambers). MBTOC continues to identify the for replacing between 30 and 45% of QPS uses with immediately available alternatives and considers that Parties may wish to step up efforts to reduce and replace QPS uses, particularly those for pre-shipment uses.

Pre-shipment uses are against endemic pests, and thus do not have the same need for the same level of pests control as quarantine treatments. This means alternatives are more readily available and that the risk from survival of a pathogen is much less. If also means that the importing country is not as concerned about the risk, otherwise they would set up a bilateral quarantine regulation for official control of the pest. In this case the treatment is no longer a pre-shipment treatment and MB would be allowable under the quarantine exemption.

Since the MBTOC 2018 Assessment Report (MBTOC, 2019), several Parties have made significant technical advances and taken strict policy decisions leading to reductions and even phase-out of MB for some QPS applications. Such policies may go further that agreed per Montreal Protocol control measures and are mainly driven by concerns for worker safety and local air quality. New Zealand has recently revised its policy of requiring recapture for all QPS uses of MB and has approved EDN, a fumigant with excellent potential to replace a MB used to treat logs.

Quarantine treatments for host plants of potentially damaging plant quarantine pests are generally approved on a pest and product specific basis following extensive bilateral or regional negotiations, which may require years to complete. This process helps ensure safety against the incursion of harmful pests. Replacing MB for quarantine treatments can be complex, as often it has long been a proven, well recognized, cost effective and readily available treatment. Many non-MB treatments are, however, published in countries quarantine regulations, and research results are encouraging users to accept and adopt alternative QPS treatments.

Since the 2018 Assessment report acceptance under domestic quarantine (biosecurity) protocols, bilateral arrangements and IPPC regulations of a number of technical alternatives as effective as MB for specific commodities has increased. These include irradiation, cold and heat treatments, modified atmospheres, phosphine, systems approaches, SF, EDN and ethyl formate.

Global production of MB reported for QPS purposes in 2021 was 10,740 tonnes, a similar amount to the level used over the previous 4 years. Although there is some variation in reported QPS production and consumption on a year-to-year basis, there is no obvious long-term increase or decrease.

Production of MB for QPS was only reported by five parties in 2021: China, India, Israel, Japan and USA.

In 2009, the QPS consumption exceeded non-QPS for the first time, being 46% higher. By 2017, reported QPS consumption was 70 times larger than controlled consumption and by 2021 over 250 times greater.

In the period between 2015 and 2021, 55 parties reported consumption of MB for QPS purposes, however 17 of these parties account for over 90% of the global reported QPS consumption. The remaining 38 countries report consumption below 50 tonnes, often much lower amounts and often not every year. MB users for QPS can be classified in four groups as follows: Big consumers with a reduction trend (Japan and China); medium consumers with an increasing trend (Australia, Egypt, India, México, New Zealand, Vietnam); small consumers on a downward trend (Brazil, Chile, Indonesia and Thailand); And small consumers with a stable or slightly upward trend (El Salvador, Malaysia, Korea).

Research programs globally are continuing to find alternatives to replace MB. The successful application of these alternatives for QPS uses would accelerate the decline in stratospheric MB levels with a near-term impact on the stratospheric ozone layer recovery. MBTOC considers Q and PS to have different priority for use of MB with PS uses having greater potential for adoption of alternatives.

In 2021, global consumption was reported at 10,465 tonnes, with A5 Parties accounted for 57% (down from 67% in 2017) and non-A5 Party consumption to 43%, (up from 31% in 2017). Nevertheless, global QPS consumption remains relatively stable around 10,000 t.

On a regional basis, since 1999 consumption in the Latin America and the Caribbean, Africa and Eastern Europe regions has remained much lower since 1999 than in Asia and in North America (including both A5 and non-A5 parties accounted for 48% of global QPS consumption, down from 55% in 2017; Australia and New Zealand for 15% North America (US + Canada) increased from 26% in 2017 to 37.5% in 2021.

While there remain some data gaps and uncertainties, information supplied by the Parties in 2018 and 2022 allowed MBTOC to estimate that five uses consumed more than 80% of the MB used for QPS in 2021: 1) Logs; 2) Pre-plant soils use; 3) Sawn timber and wood packaging material (ISPM-15); 4) Grains and similar foodstuffs; and 5) Fresh fruit and vegetables. These are the same categories as in 2018, but proportions have changed. On the basis of these estimates and currently available technologies to replace MB for QPS, MBTOC has estimated that between 30 and 45% of the MB used for QPS purposes could be replaced with immediately available alternatives.

Ethane dinitrile has recently been registered as an MB alternative for export logs in New Zealand and can potentially reduce MB use substantially. Sulfuryl fluoride, a common timber and structural fumigant for termites is also effective, however, environmental issues (very high GWP) and the difficulty with efficacy against insect eggs cannot be overlooked.

For pre-plant soil quarantine treatments of various types of nursery materials, alternative fumigants are available, which can meet certification standards; substrates also may be used at least partially in the propagation systems.

For perishables, there are various approved treatments, depending on product and situation, including heat (as dry heat, steam, vapour heat or hot water dipping), cold (sometimes combined with modified atmosphere), modified and controlled atmospheres, alternative fumigants (e.g. ethyl formate), physical removal, chemical dips and irradiation. Irradiation of fresh food continues to grow in trade between countries.

In the absence of regulatory or economic incentives to adopt alternatives, MB is often the lowest cost effective option at present, an alternative would not be voluntarily adopted unless it performed as well or better at a similar or more economic market cost.

With the aid of the Ozone Secretariat, MBTOC has taken steps to reactivate the Memorandum of Understanding (MOU) between the Ozone Secretariat and the International Plant Protection Convention (IPPC), which was drawn in 2012. The IPPC has now approved and published 26 international approved non-MB treatments in recent years for use on a combination of fresh produce, wood or pest specific treatments through the work of the TPPT.

MBTOC keeps track of efforts made by IPPC and its subsidiary bodies to replace MB use for quarantine purposes as far as possible without losing the high degree of control in the various fields of application.

1.8. Emissions from methyl bromide use and their reduction

The large reduction (99%) in the reported consumption of MB (MB) since 1999 for controlled non-QPS uses has resulted in a significant decline in atmospheric emissions of MB. Since the peak in emissions of MB of around 50,000 tonnes in 1998, anthropogenic emissions of MB have declined by approximately 71% with stratospheric MB concentrations as measured in the southern hemisphere falling from a peak of 8.5 ppt to present 2021 levels of around 6.0 ppt. The reduced consumption and the related emissions of MB to date, has been responsible for the present fall of approximately 30% in Effective Equivalent Stratospheric Chlorine (EESC), thus contributing to a similar gain to the present recovery of the ozone layer. Annual (2021) emissions from remaining uses are c. 8505 t MB, being about 8455 t from QPS uses and 73 tonnes from CUEs with minor amounts, probably less than 100 t, from the 4,000 t used for feedstock. There is a potential further gain of 10% to the present ozone layer recovery if these emissions were to be eliminated.

MB emissions to the atmosphere from known usage of MB have remained relatively stable since the last Assessment in 2017. MBTOC estimates that a large proportion of the MB used for QPS applications is emitted (83% on average, with wide variation between different applications) and this is released directly to the atmosphere. The remainder of applied MB is converted to non-volatile reaction products and retained in the treated materials and associated packing and structures.

The reduction of emissions of MB to the atmosphere to date has been due mostly to adherence in most cases to phase out schedules under the Montreal Protocol under Annex E for non A5 Parties by 2005 and A5 parties by 2015, and almost complete reductions for MB use presently being requested under the Critical Use exemption process.

There has been an unexplained rise in MB mole fraction in the atmosphere to 6.0 ppt in mid-2020, one of three small fluctuations observed since 1998. These small fluctuations do not correspond fully with variation in the reported annual global MB production and consumption and the resultant emissions. Some studies report that the unexplained part of the gap in the top down to bottom up estimate of emissions may be due to climate impacts and La Nina events, others suggesting that production and consumption not be being fully reported or sources fully known from some regions globally. A recent review of the global budget of sources and sinks of MB (both natural and anthropogenic) concluded that the fact that the budget gap declined during phase-out as anthropogenic emissions decline, suggests that at least part of the gap results from underestimation of past anthropogenic emissions.

As nearly all uses of MB for fumigation are now nearly all from QPS uses there is opportunity on a technical basis, to control the remaining emissions of MB from fumigations either by adopting recapture/destruction technologies for current QPS structural and commodity fumigations or by adopting non-ODS alternatives. MBTOC estimates that in 2021, 7955 tonnes of MB were emitted from QPS commodity treatments, with about 4296 t available in practice for recapture/destruction. The balance of applied MB that is unavailable for recapture is either lost through reaction to non-ODS degradation products (c.15%) or inadvertently leaked to the atmosphere during and after the fumigation treatment.

Emissions of MB from remaining CUE and QPS soil treatments are considered to be around 500 t. However, these treatments are not suitable to recapture/destruction technologies. MBTOC considers that barrier films are the best way to redcuce emissions and should be mandatory. MBTOC also notes that emissions from these applications could be avoided by adoption of alternative non-MB treatments.

MBTOC notes that a number of Decisions urge Parties to minimise emissions of MB and to use MB recovery and recycling technology where technically or economically feasible for QPS treatments until alternatives to MB are available e.g. (Decisions VII/5, XI/13). Some countries and local jurisdictions have regulations in place, or proposed, to minimise MB emissions from fumigation operations through use of recapture and/or destruction technologies, but these have mainly been issued in relation to local air quality, not ozone layer protection.

A variety of recapture/destruction systems for space fumigations (commodity and structures) are available commercially or at an advanced stage of development. In 2021, total recapture of MB from fumigations is considered to unlikely to have exceeded 100 t annually. MBTOC notes that quantities of MB recaptured or destroyed are not routinely reportable unless by an Approved Destruction Process.

Reduction in emissions for all remaining uses of MB for QPS, together with identification and stopping any unreported uses are considered important factors to return MB concentrations in the atmosphere to natural levels. Owing to the relatively short lifetime of MB in the atmosphere (0.7 years), adoption of any suitable alternatives and in some cases adoption of recapture/destruction would have an immediate benefit in reducing atmospheric MB levels. It is an important opportunity available to Parties to rapidly enhance ozone layer recovery, with effects of reducing emissions from QPS observable in the stratosphere within 2 years.

1.9. Economic issues

No CUN has to date relied solely on an argument of economic infeasibility to argue for an exemption. Nevertheless, MBTOC analyses any arguments and calculations about the economics of the use of MB alternatives put forward by a Party because it is always possible that MBTOC may recommend against an exemption on technical grounds but find that economic factors mitigate against the use of alternatives. This is in addition to the conventional notion that the use of an alternative to MB may be technically feasible, but that it may turn out to be economically infeasible.

As noted in previous Assessment Reports, it is sufficient in most cases to use **partial budgets** to assess economic feasibility.

2

2. Introduction to the Assessment

2.1. Introduction

Under Decision XXXI/2 taken at the Thirty-First Meeting of the Parties to the Protocol in 2019, the Parties requested the Assessment Panels to update their 2018 reports in 2022 and submit them to the Secretariat by 31 December 2022 for consideration by the Open-ended Working Group and by the Thirty Fifth Meeting of the Parties to the Montreal Protocol, in 2022.

The MBTOC 2022 Assessment reports on advances since 2018 to replace Methyl Bromide (MB), now exclusively used under Critical Use by both A5 and non-Article 5 Parties. It also reports on QPS uses, which are presently exempt from controls under the Montreal Protocol. It covers technically and economically feasible alternatives for non-QPS and QPS uses of MB and gives actual examples of their successful commercial adoption around the world. It shows trends in methyl bromide production and consumption in both Article 5 and non-Article 5 Parties, estimated levels of emissions of MB to the atmosphere, and strategies to reduce those emissions.

The control measures, agreed by the Parties at their ninth Meeting in Montreal in September 1997, were for phase out by 1 January 2005 in non-Article 5 countries and for Parties operating under Article 5 of the Protocol (developing countries) a 20% cut in production and consumption, based on the average in 1995-98, from 1 January 2005 and phase out by 1 January 2015. After these dates MB use for controlled uses has only been allowed under the Critical Use Exemption (CUE). In 2003, nine non-Article 5 Parties submitted nearly 150 applications for 18,700 tonnes for 'critical uses' after 2005 for non-QPS purposes under Article 2H of the Montreal Protocol. By 2022 the number has declined to two applications for about 20 tonnes for use in 2023 and 2024. Use of methyl bromide under the 'Critical Use' provisions became available to Article 5 parties in 2015 and presently, only one A5 Party has requested MB under the CUE for use in 2023, totalling 19 tonnes.

2.2. Global overview of methyl bromide uses as a fumigant and industrial chemical

MB has been used commercially as a fumigant since the 1930's (MBTOC, 1994). It is a highly versatile product, used in many different applications, for the control of soilborne pests (nematodes, fungi, weeds, insects) in high-value crops, and for the control of insects, rodents and other pests in structures, transport and stored commodities. MB has features that make it a versatile biocidal with a wide range of applications. In particular, it is a gas that is quite penetrative and usually effective over a broad range of temperatures. Its action is usually sufficiently fast and it airs rapidly enough from treated systems to cause relatively little disruption to crop production or commerce.

2.2.1. MB uses identified in Articles of the Protocol

MB was listed under the Montreal Protocol as a "controlled substance" in 1992 (Article 1 and Annex E). The Articles of the Protocol refer to four main categories of MB uses, and each is subject to different legal requirements. Table 2-2 lists these four categories and indicates those for which information is provided in this MBTOC report. Additional control schedules were agreed to in 1995 and 1997 for two of the categories - the non-QPS fumigant uses and laboratory and analytical (L&A) uses under Articles 2 and 5, with authorised Critical Use Exemptions (CUE). The phase-out schedules are summarized in Table 2-1 below.

TABLE 2-1: PHASE-OUT SCHEDULES AGREED AT THE NINTH MEETING OF THE PARTIES IN 1997

Year	**Non-Article 5 countries**	**Article 5 countries**
1991	Consumption/ production baseline	
1995	Freeze	
1995-98 average		Consumption/ production baseline
1999	25% reduction	
2001	50% reduction	
2002		Freeze
2003	70% reduction	Review of reductions
2005	Phaseout with provision for CUEs	20% reduction
2015		Phaseout with provision for CUEs

Source: Montreal Protocol Handbook, UNEP, Ozone Secretariat 2018.

Critical and emergency uses may be permitted after phaseout if they meet agreed criteria. Emergency uses may be of up to 20 metric tonnes under Decision IX/7. Parties are urged to use stocks of MB for their critical uses. Such stocks need to be reported to the Ozone Secretariat, only when a Party has requested a CUN.

Quarantine and pre-shipment (QPS) uses and feedstock are exempt from reductions and phaseout but are subject to reporting requirements under the Protocol. Feedstock is mentioned in this report only when discussing statistics on global MB production for all uses in Chapter 3. Laboratoty and Analytical (L&A) uses are also included in general statistics on MB production in Chapter 3 but no breakdown is available. L&A uses are not discussed in MBTOC reports because they are assessed in the reports of the Medical and Chemical Technical Options Committee (MCTOC).

Because the phase-out of controlled uses (non-QPS) of MB is now almost complete, QPS uses now comprise about 97.5% of MB use by the Parties of the Montreal Protocol (see Chapter 5). QPS use of MB has thus become the largest, non-controlled ODS emission (among the substances presently included in the Montreal Protocol).

TABLE 2-2: CLASSIFICATION OF MB USES UNDER THE MONTREAL PROTOCOL, INDICATING RELEVANT SECTIONS IN THIS ASSESSMENT REPORT

MB uses	Status under the Montreal Protocol	Relevant information in MBTOC 2022 Assessment
Non-QPS fumigant uses	Subject to production and consumption phase-out schedules of Articles 2 and 5, trade and licensing controls of Article 4, and data reporting requirements of Article 7. Critical Use Exemptions can be authorised by the MOP for specific uses that meet the criteria in Decision IX/6 and other relevant decisions in Article 5 and non-Article 5 Parties. Additionally some Parties have used small amounts of methyl bromide (< 20 t) after 2005 under the 'Emergency Use' provisions under Decicion IX/7 of the Montreal Protocol.	Chapters 1-2 and 6-7
QPS fumigant uses	Exempted from reduction and phase-out schedules. Subject to Article 7 data reporting requirements	Chapter 5
Laboratory and analytical uses	Subject to production and consumption phase-out schedules of Articles 2 and 5 except for the specific Critical Use Exemptions under Decision XVIII/15. Subject to data reporting under Annex II of the 6th Meeting of the Parties	L&A uses are covered in MCTOC reports. Chapter 3 statistics on MB production include L&A, but no breakdown is available
Feedstock used in the manufacture of other chemicals	Exempted from phase-out schedule under Article 1. Subject to Article 7 data reporting requirements	Chapter 3 statistics on MB production

Recently, during its 18th meeting, the Chemical Review Committee (CRC) of the Rotterdam Convention held in September 2023 recommended that methyl bromide be listed under Annex III of the Rotterdam Convention, which includes pesticides and industrial chemicals that have been banned or severely restricted for health or environmental reasons (CRC, 2022). If the Conference of the Parties to this convention accepts this recommendation, then MB will be subjected to the Prior Informed Consent procedure enabling its 165 parties to share information and responsibility and take decisions on potential future imports. MBTOC will continue to watch this issue closely and assess its impacts on MB use and availability (Rotterdam Convention CRC, 2022)

2.3. MBTOC mandate

The Methyl Bromide Technical Options Committee (MBTOC) was established in 1992 by the Parties to the Montreal Protocol to identify existing and potential alternatives to MB. MBTOC, in particular, provides recommendations and advice to the Parties on the technical and economic feasibility of chemical and non-chemical alternatives for MB. Effectively, MBTOC work is related to phaseout of MB used as a fumigant.

Additionally, from 2003, MBTOC has had the task, under Decision IX/6 and others, of evaluating Critical Use Nominations submitted by non- Article 5 Parties to the Montreal Protocol and by Article 5 Parties from 2014. MBTOC provides recommendations on such nominations, for review and endorsement by the Technology and Economic Assessment Panel (TEAP) and then consideration by the Parties. MBTOC presently works as a single committee and its members have distinct expertise in the uses of MB and its alternatives following areas: Soils (pre-plant fumigation), Structures and Commodities (SC), Recapture and Destruction and Quarantine and Pre-Shipment (QPS). MBTOC also has expertise in MB production and consumption data and agricultural extension.

MBTOC is a subsidiary body of TEAP, the Panel that advises the parties on scientific, technical and economic matters related to ozone depleting substances and their alternatives. Information contained in MBTOC's reports contribute to the Parties' deliberations on appropriate controls for MB and its alternatives and for endorsement of use by the Parties for critical uses. Parties review MBTOC and TEAP's recommendations and may accept, reject of modify these recommendations when taking decisions on CUE requests.

2.4. Committee process and composition

As of December 2022, MBTOC has 16 members; nine (56%) from non-Article 5 and seven (44%) from Article 5 Parties. These members come from seven Article 5 and eight non- Article 5 countries. Representation from diverse geographic regions of the world promotes balanced review and documentation of alternatives to MB, based on the wide-ranging expertise of Committee members. MBTOC members may be nominated by their governments; MBTOC co-chairs also have the authority to appoint members in full consultation with the focal points from their country of origin.

In accordance with new and revised Terms of Reference for TEAP and its Technical Options Committees, (Decision XXIII/10 (9)) terms of service are now set at four years with the option of reappointment for ensuing terms.

In accordance with the terms of reference of TEAP and TOCs, MBTOC members participate in a personal capacity as experts and do not function as representatives of governments, industries, non-government organisations (NGOs) or others (Annex V of the report of the 8th Meeting of the Parties). Members of MBTOC contribute substantial amounts of work in their own time. For construction of this Assessment Report, MBTOC met virtually in April 2022 and in person in Bonn, Germany (September, 2022). To produce each chapter as efficiently as possible, MBTOC members worked primarily on chapters covering their specific topics, and topics affecting all chapters were discussed and agreed by the entire committee. Assessment structure and contents were agreed during these and previous formal meetings. The Assessment was finalised by email, to produce a consensus document of the Committee, which was submitted to the Ozone Secretariat for posting at their website.

2.5. MBTOC Assessments on methyl bromide

The first interim assessment on MB for the Protocol was completed in 1992. A full assessment of the alternatives to MB was completed in 1994 and reported to the Parties in 1995 (MBTOC, 1995) as a result of Decisions taken at the fourth Meeting of the Parties to the Montreal Protocol held in 1992. The second MBTOC Assessment was presented to Parties in 1998 (MBTOC, 1998), the third in 2002 (MBTOC, 2002), the fourth in 2006 (MBTOC, 2007) the fifth in 2010 (MBTOC, 2011), the sixth in 2014 (MBTOC, 2015) and the seventh in 2018 (MBTOC, 2019). The 2022 Assessment Report is MBTOC's eighth.

MBTOC progress reports on advances in alternatives to methyl bromide and other issues related to methyl bromide are included in annual TEAP reports to the Parties. MBTOC further produces reports on its assessment of CUNs twice a year: one interim and one final report. These reports can be found on the Ozone Secretariat website at http://ozone.unep.org/teap/Reports/MBTOC/index.asp .

Under Decision XXI/2 (2) taken at the Thirty-First Meeting of the Parties to the Protocol in 2019, the Parties requested the Assessment Panels to update their 2018 reports in 2022 and submit them to the Secretariat by 31 December 2022 for consideration by the Open-ended Working Group and by the Thirty-Fifth Meeting of the Parties to the Montreal Protocol, in 2023. This MBTOC 2022 Assessment Report primarily provides an update on advances since 2018.

2.6. Definition of an alternative

In this report, following guidance given in Annex 1 of 16 MOP report, MBTOC defined ‘alternatives’ as:

> *' any practice or treatment that can be used in place of methyl bromide. 'Existing alternatives' are those alternatives in present or past use in some regions. 'Potential alternatives' are those in the process of investigation or development.*
> *MBTOC assumed that an alternative demonstrated in one region of the world would be technically applicable in another unless there were obvious constraints to the contrary e.g., a very different climate or pest complex.*

This definition of ‘alternatives’ is consistent with that used in previous Assessments.

MBTOC is not required in its terms of reference to conduct economic studies on MB and alternatives, however annually it reports on the Parties economic statements on MB and alternatives when requesting CUEs. As per Decision IX/6 and others, alternatives to MB must be technically and economically feasible. Additionally, it was recognised that regulatory requirements, environmental issues and social constraints may make an alternative unavailable in a specific country or region. MBTOC reports on CUNs do fully consider the availability or lack of availability in specific locations.

2.7. Report structure

In addition to the *Executive Summary* (Chapter1) and this Introductory Chapter (Chapter 2), the assessment report contains the following chapters:

Chapter 3: Methyl bromide production, consumption and progress in phase-out provides statistics on MB production, consumption and major uses from 1991 to the present day, including controlled and exempted uses. The chapter provides a brief overview of the major trends, discusses MB production and supply, and provides a historic perspective of MB uses. It focuses on QPS uses including trends of MB production and consumption, which is the current remaining use of MB except for small CUEs granted by the parties.

Chapter 4: Methyl Bromide Emissions and Emissions Reduction discusses:

- Atmospheric methyl bromide – Global sources and emissions
- Impact of Montreal Protocol control measures on global MB emissions
- Emissions from current uses for soil, commodities and structures
- Emission reduction through better containment, recapture or destruction
- Efficiency of recapture
- Developments in MB recapture with recovery and recycling systems

Chapter 5: Alternatives to methyl bromide for QPS applications covers MB and alternative treatments for Quarantine and Pre-shipment (QPS) of durable and perishable commodities, including discussion of:

- Categories of use
- Key quarantine pests controlled with MB
- International (IPPC) standards influencing MB use for quarantine
- Existing and potential alternatives to the main categories of MB use for QPS purposes.
- Reducing emissions and improving efficiency of MB treatments
- Constraints to adoption of alternatives and remaining challenges

Chapter 6: Alternatives to Methyl Bromide for soil treatment covers a range of alternatives for pre-plant soil fumigation, focusing on:

- ➢ Non-chemical alternatives: biological and physical alternatives
- ➢ Chemical alternatives : fumigant and non fumigant pesticides
- ➢ New practices and technologies: innovative technologies with plastic mulch films, new formulations of fumigants, 3-site specific fumigant management, disinfestation with steam in California strawberry nurseries, chlorine dioxide (ClO2), granules as an alternative to MB,
- ➢ Integrated Pest management
- ➢ Alternatives for the remaining MB critical uses in the soil sector
- ➢ Remaining and emerging challenges impacting MB phase-out for soils use
- ➢ Impacts of some chemical and non-chemical alternatives to methyl bromide adopted in the soil sector, on the sustainable development goals (SDGs): MB emissions, copper use in organic agriculture, plastic mulching films, the release of Dinitrous Oxide (N2O) in the atmosphere by ASD, energy consumption by microwaves

Chapter 7: Alternatives to methyl bromide for structures and commodities provides a historic perspective on alternatives adopted for past key SC uses, alternatives for remaining controlled uses in the SC sector and an update on MB alternatives research including for high moisture dates, cure pork and aircraft, plus a review on pest egg control with sulfuryl fluoride and Integrated Pest Management.

Chapter 8: Economic issues provides a brief description of economic information furnished by the Parties when submitting CUNs and the economic analysis undertaken by MBTOC, together with a review of recent publications on the matter.

Appendix 1 contains a list of MBTOC members, area of expertise, country of origin and affiliation.

Disclosure of Interest (DOI) statements can be found at the Ozone Secretariat website and are updated once a year at minimum, or sooner if a members' situation changes in a manner that is relevant to the DOI.

Appendix 2 provides a comprehensive list of lethal conditions to control various species and developmental stages of pest insects

2.8. References

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3

3. Methyl Bromide Production, Consumption and Progress in Phase-out

3.1 Introduction

This chapter provides statistics on MB production, consumption and major uses from 2000-2020, compared in some cases with the 1991 baseline, for both non-exempted (controlled) and QPS uses generating anthropogenic emissions to the atmosphere.

Under the Protocol, MB consumption at the national level is defined as '*production plus imports minus exports, minus QPS, minus feedstock'*. It thus represents the national supply of MB for uses controlled by the Protocol (i.e. non-QPS)[1].

3.2. Methyl bromide global production and supply

The information on MB production is compiled from the reports submitted by Parties, expressed in metric tonnes. Table 3-1 below shows the global trends.

Table 3-1: Reported MB production for all purposes, in 1991 baseline and 2000-2021 (metric tonnes).

YEAR	For controlled uses	For QPS uses	For chemical feedstock[2]	For Laboratory/ Analytical Uses	Total Production
1991 (baseline)	**66428.8**	**3529.6**	**3610**	**0**	**73568.4**
2000	45948.6	9792.9	13132	0	68873.5
2001	34400.2	9496.2	3190	0	47086.3
2002	28356.5	11268.8	4331	0	43956.3
2003	25538.5	10246.2	6759	0	42543.7
2004	24635.8	10659.6	8012	0	43307.5
2005	18138.8	13815.4	5014	0	36968.3
2006	19628.2	10274.9	4475	0	34378
2007	12876.8	12983.9	5224	0	31084.7
2008	10784.3	8374.5	5097	0	24255.8
2009	11166.2	8944.6	6408	0	26518.8
2010	7493.7	11777.5	7340	0.0002	26611.1
2011	4555.2	9435.7	5148	0	19138.9

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[1] Consumption may be different from actual use as MB imported in a particular year may be consumed in another. Further, stocks of MB already accounted for as consumption may be used in later years.

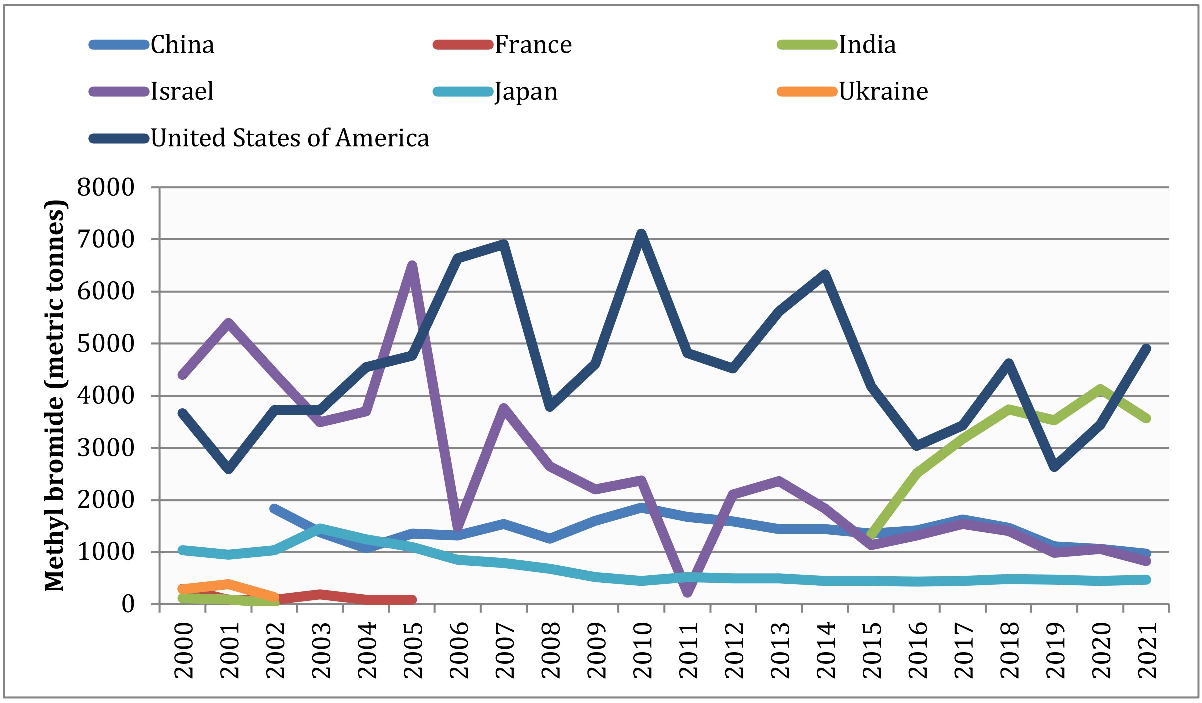
[2] MB is sometimes used as a feedstock, for example introducing it into an industrial process to synthesize a new compound, in combination with other chemicals. This use is permitted as the MB is transformed into another substance.

YEAR	For controlled uses	For QPS uses	For chemical feedstock[2]	For Laboratory/ Analytical Uses	Total Production
2012	4005.5	8723.4	4446	0	17174.9
2013	2492.7	9915.2	5662	0.00351	18069.9
2014	1030	10058.7	4829	0.01506	15917.7
2015	658	8448.7	3927	0.021	13033.7
2016	900.2	8713.8	4326	0.005	13939.9
2017	297.3	10155.6	3031	0	13484
2018	-48.7*	10850.8	2723	0	13524.9
2019	-4.3*	8723.9	3338	0.03066	12058.1
2020	-62*	10142.5	3061	0.02327	13141.7
2021	-38.66*	10736.8	2267		12173**

*Negative values for a given year imply that quantities destroyed or quantities exported for feedstock uses exceeded production for that year, implying that the destroyed or exported quantities were taken from stockpiles. Source: Database of Ozone Secretariat as of September 2022.

In 2017 the reported **MB production for QPS** was 10155.6 metric tonnes representing 75% of total global MB production for all purposes, including feedstock. In 2021, 100% of reported MB production, was for QPS purposes and feedstock use, and production for controlled uses was zero. Fig. 3-1 below shows the evolution of the remaining Parties reporting MB production for QPS uses.

Fig. 3-1: Production of MB for QPS uses 2000-2021 in China, India, Israel and US



Source: Ozone Secretariat Data Access Centre 2023.

Since 2018 no Party reported production of MB for controlled uses (non-QPS)[3]. However, MBTOC notes once again that MB is still offered on the internet for any use, including soil fumigation and treatment of stored products. An example is *Sartichem Ltd*. (www.sarthichem.com[4]) a company established in India in 2004, that openly offers methyl bromide in 98:2 formulation in cylinders of several sizes for export around the world. MB has also been used for critical use purposes since 2018, yet no procduction has been identified for that use.

3.3. Methyl bromide trends in global MB consumption

On the basis of Ozone Secretariat data, consumption for controlled uses was estimated to be about 64,420 tonnes in 1991, it was reported to fall to about 2953 tonnes in 2013; 245 tonnes in 2017 and has plummeted to negative figures in 2021 as illustrated in Figure 3-2. In 2021, reported MB consumption for controlled uses was around 40 tonnes, although stocks substantially higher than this may be used in some sectors in various countries. While stocks are only presented by Parties requesting CUNs, four of them reported stocks of around 50 metric tonnes at the end of 2019 and 6 tonnes at the end of 2021. Total stocks are unknown, as they are not required to be reported from all parties[5].

After nearly 20 years of applications for critical uses, the amount of methyl bromide requested has fallen from 18,700 tonnes for 2005 to 40 tonnes submitted for either 2023 or 2024. In the 2022 round of nominations, two Parties, Canada and Australia, continue to make small critical use nominations for strawberry runners pre-plant soil fumigation. A CUE was approved by the parties for structures and dwellings in South Africa in 2023. More detailed information on CUEs can be found in TEAP/MBTOC CUN reports (TEAP 2021 and 2022).

It is thus clear from Fig 3-2 that present consumption of MB is for QPS uses (approx.10,000 p.a.) and therefore, if stocks are excluded, that almost 100% of the anthropogenic MB emitted to the atmosphere is related to quarantine and pre-shipment uses.

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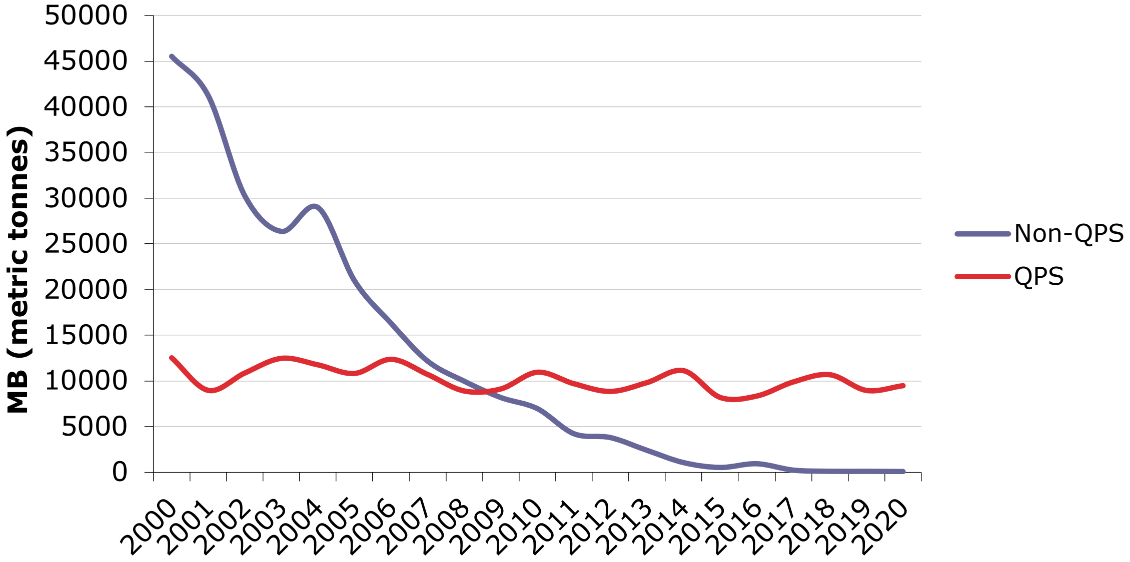
[3] For this Assessment, no report indicates any production, or lack of availability of reliable data.

[4] Accessed in September 2022

[5] MBTOC considers that these latter stocks may be substantial (approximately 1200 tonnes).

FIG. 3-2: TRENDS IN MB CONSUMPTION FOR CONTROLLED AND EXEMPTED USES FROM 2000 TO 2021 (METRIC TONNES)



Source: Ozone Secretariat Data Access Centre 2023.

3.3.1 Methyl bromide trends in Quarantine and Preshipment MB consumption

Over the past decade, some Parties have succeeded in completely phasing out MB for QPS uses. However, the overall global consumption for QPS has not changed markedly since other Parties have increased their consumption substantially. When analysing the Ozone Secretariat´s database, the first point of note is that global QPS consumption remained relatively stable over the 2000-2021 period at an average of around 10,000 metric tonnes per year.

When considering the more recent 2015-2021 set of data, a second conclusion is that from the 198 signatory countries of the Montreal Protocol only 55 report that they are using MB for QPS uses[6].

Taking into account its importance in global trade, one significant absence from this list is that of the European Union. In fact, all member states of the EU banned all MB uses (for both controlled and QPS) as of 2010 (OJEU, 2008), although some treatments abroad could still be required for some imported goods (UNEP, 2016).

The third important fact arising from data available (2015-2020) is that only 17 countries contribute to about 94% of the reported QPS consumption: Australia, Brazil, Chile, China, Egypt, El Salvador, India, Indonesia, Japan, Mexico, Malaysia, New Zealand, Pakistan, Republic of Korea, Thailand, United States of America and Viet Nam (Fig 3-3). The other 38 Parties use less than 50 tonnes per year and most of them do it in very small amounts and/or not every year.

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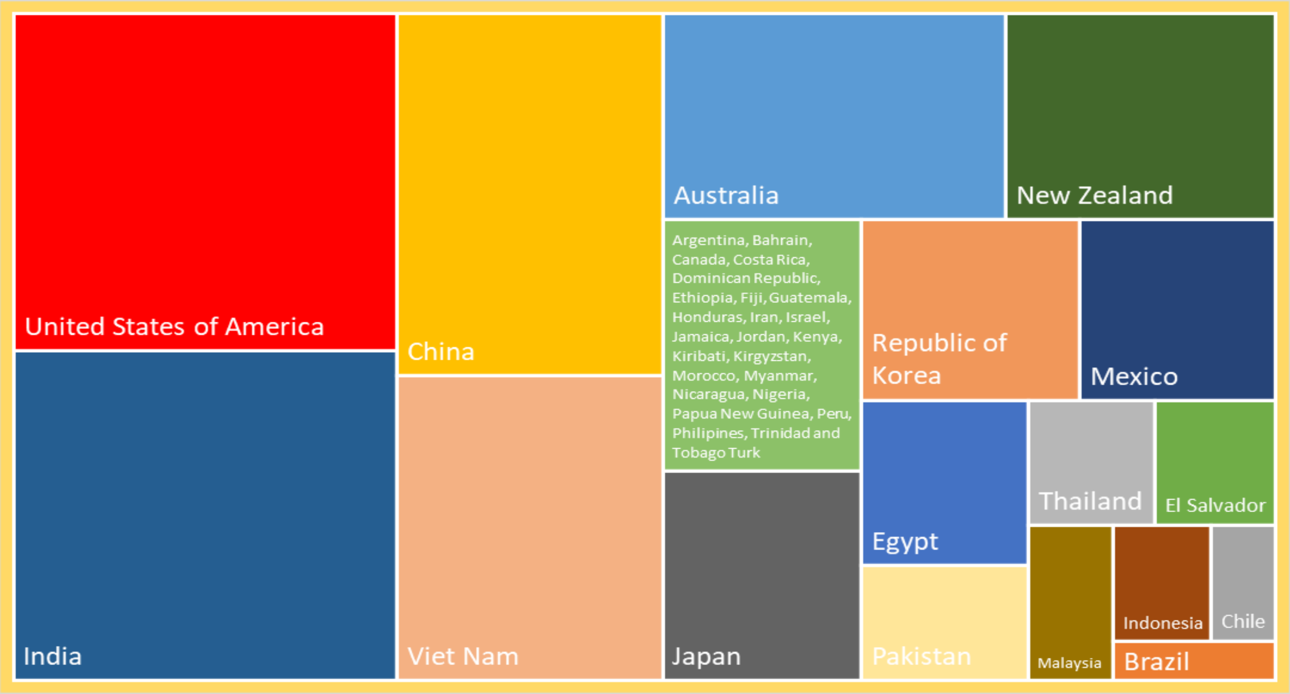
[6] For this Assessment, no report indicates no consumption or lack of availability of reliable data.

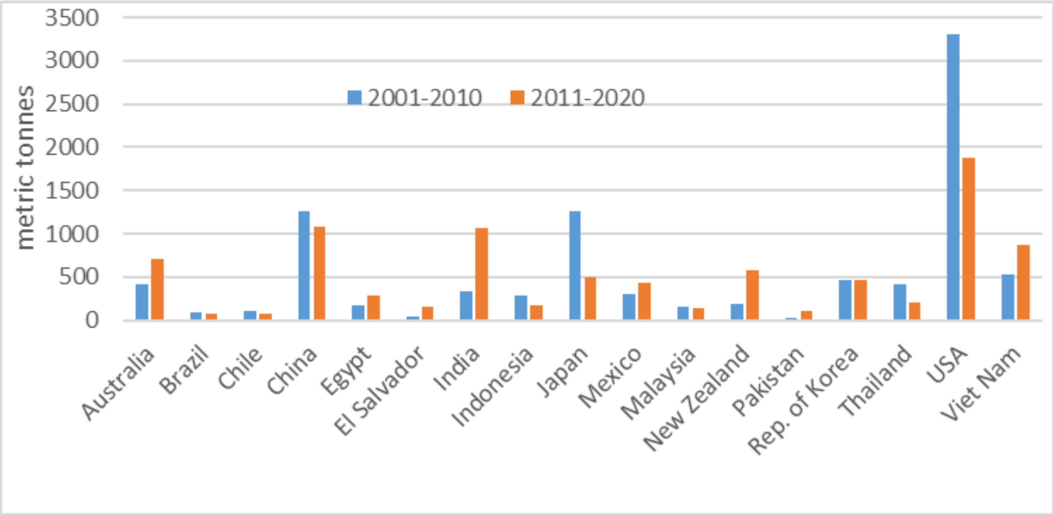
Fig. 3-3: Methyl bromide QPS consumption proportion of 17 main consumers and other Parties of the Montreal Protocol (average 2015-2020)



Total graph area represents 100% of reported QPS consumption average from 2015 to 2020
Source: Ozone Secretariat Data Access Centre 2022

Even though onsumption for QPS concentrates in a small number of parties, evolution of consumption patterns in each of these parties has been different in the last two decades as seen in Fig. 3-4.

Fig. 3-4: Trends in MB consumption for QPS uses from 2001-2010 and 2011-2020 (metric tonnes) for the main consuming parties



Source: Ozone Secretariat Data Centre, 2022 (UNEP, 2022)

With these indicators, it is possible to roughly classify the main QPS methyl bromide user countries in 4 groups:

a) <u>Big consumers with a reduction trend</u>: US, Japan and China

b) Medium consumers with an increasing trend: Australia, Egypt, India, México, New Zealand and Vietnam.
c) Small consumers with a reduction trend: Brazil, Chile, Indonesia and Thailand
d) Small consumers with a slightly upward trend: El Salvador, Malaysia and the Republic of Korea

Some of these Parties show dramatic increases in their use. Between 2005 and 2021, for example, Australia increased its QPS use from 358 to 641 metric tonnes (over 90%) and New Zealand from 115 to 857 tonnes (over 700%). In the same region, India increased its QPS use from 329 tonnes in 2015 to 2104 tonnes in 2020 (539%), going down to 1554 in 2021; Pakistan increased from 68 to 368 metric tonnes (over 500%) in the same period.

At the same time, research programs globally are continuing to find alternatives to replace MB (see chapter 5 on QPS). The successful application of these alternatives for QPS uses would accelerate the decline in stratospheric MB levels with a near-term impact on the stratospheric ozone layer recovery.

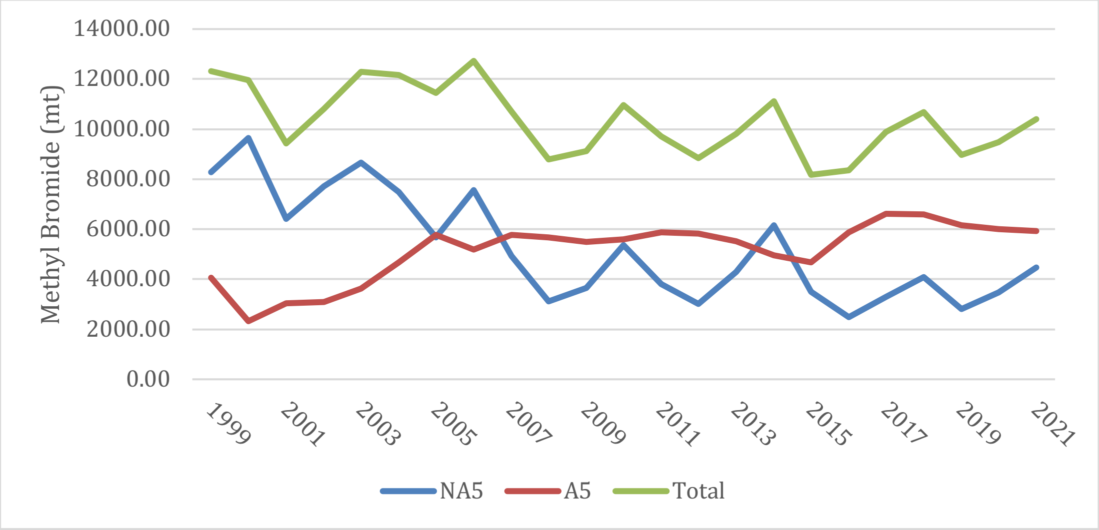
MBTOC considers Q and PS to have different priority for use of MB with PS uses having greater potential for adoption of alternatives. PS uses could potentially be phased out because there are technically alternatives which are widely available and suitable worldwide. The Montreal Protocol could accelerate implementation of these alternatives over the medium term. MBTOC considers that the readily available alternatives for PS could result in replacing 30-40% (i.e. 3000-4000 tonnes) of the total QPS MB use if the alternatives were adopted.

3.3.2. Regional QPS Consumption trends

3.3.2.1 A5 vs non-A5 consumption

In 2021, global consumption amounted to 10,465 tonnes. A5 Parties accounted for 57% of global MB consumption for QPS purposes (5,976 tonnes), down from 67% in 2017; non-A5 Party consumption, at 4,489 tonnes was 43%, up from 31% in 2017. Consumption in A5 Parties trended upward between 2015 and 2018 but that trend has changed since then (Fig. 3-5). Consumption in non-A5 Parties shows significant variation from one year to the next, with an upward trend since 2019. Nevertheless, global QPS consumption remains relatively stable around 10,000 t.

FIG. 3.5: GLOBAL, NON-A5 AND A5 CONSUMPTION OF QPS FROM 1999 TO 2021

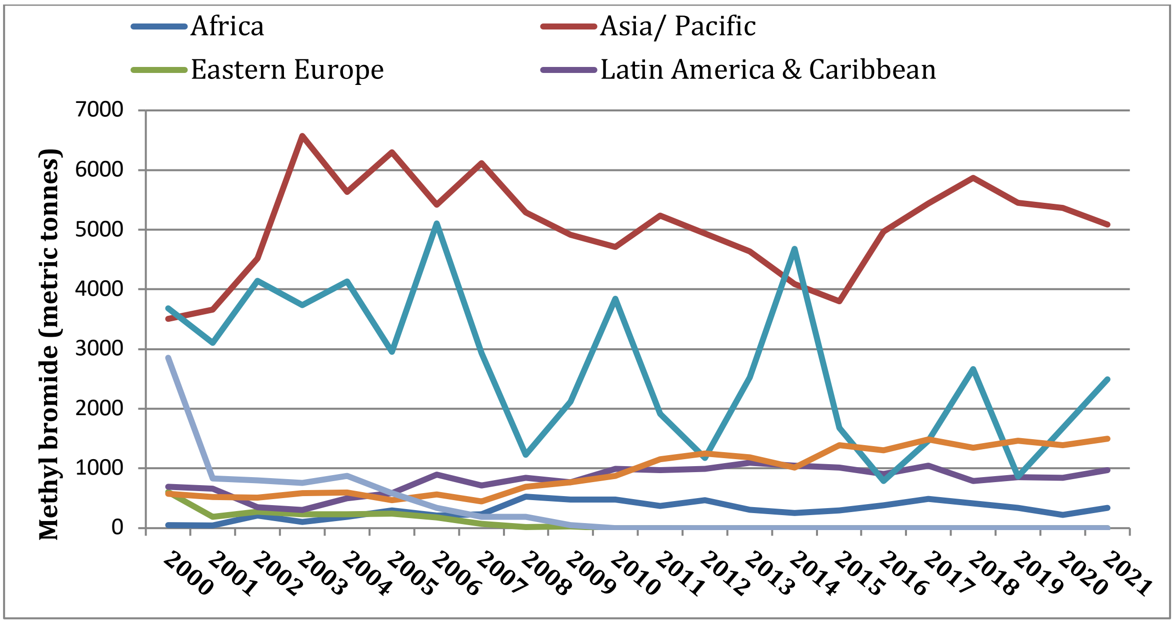


Source: Ozone Secretariat Data Access Centre, 2022

3.3.2.2 Consumption by geographical region

MBTOC further conducted an analysis consumption of MB for QPS purposes over the past two decades on the basis of data reported by Parties until 2021. The regions shown in Fig 3-6 include both A-5 and non-A5 Parties when these are located in the same region (as an example, the Asia region includes Japan, Israel, China, Indonesia, Turkey and others). Wide variations are noted for North America (the USA comprises over 99% of this consumption since Mexico has been included in the "Latin America & Caribbean region). A continued upward consumption trend is noted in Asia, which corresponds mainly to A5 countries in that region.

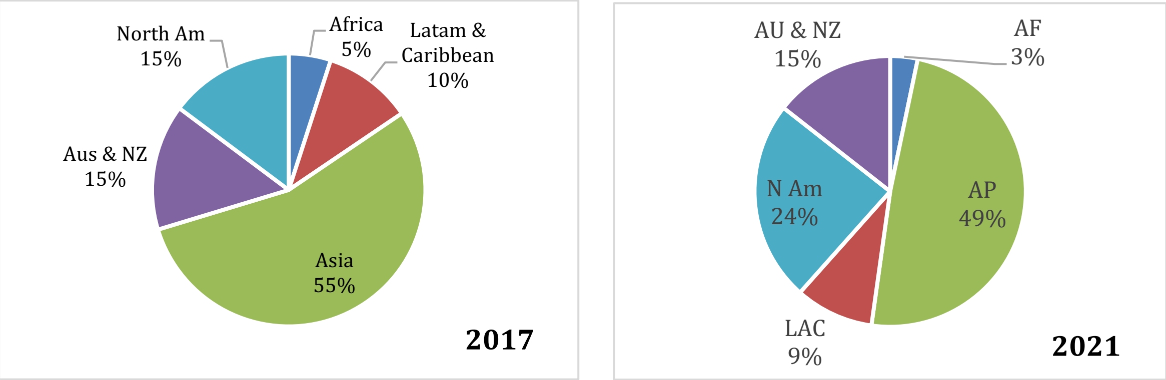
FIG. 3-6: REGIONAL CONSUMPTION OF QPS FROM 2000 TO 2021



Source: Ozone Secretariat Data Access Centre, 2022. * North America comprises USA + Canada

Consumption in the Latin America & Caribbean and Africa regions has traditionally been much lower than in Asia and North America. Between 2017 and 2021, proportions in other regions changed: In 2021 Asian parties consumed 5,090 tonnes, (including both A5 and non-A5 parties in the regions where appropriate). This corresponds to 48% of global QPS consumption, down from 55% in 2017; Australia and New Zealand account for 15% of global consumption whilst North America (US + Canada) increased from 26% in 2017 and 37.5% in 2021 (Fig 3-7).

FIG. 3-7: REGIONAL CONSUMPTION OF QPS IN 2017 (LEFT) AND 2021 (RIGHT)



Source: Ozone Secretariat Data Access Centre, 2022

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4

4. Methyl Bromide Emissions and Emissions Reduction

4.1 Summary

The large reduction (99%) in the reported consumption of methyl bromide (MB) for controlled non-QPS uses since 1999 has resulted in a significant decline in atmospheric emissions of MB. Since the peak in emissions of MB of around 50,000 tonnes in 1998, anthropogenic emissions of MB have declined by approximately 71% with stratospheric MB concentrations as measured in the southern hemisphere falling from a peak of 8.5 ppt to present 2021 levels of around 6.0 ppt. The reduced consumption and the related emissions of MB to date, has been responsible for the present fall of approximately 30% in Effective Equivalent Stratospheric Chlorine (EESC), thus contributing to a similar gain to the present recovery of the ozone layer (Porter and Fraser, 2020). Annual (2021) emissions from remaining uses are c. 8505 t MB, being about 8455 t from QPS uses and 73 tonnes from CUEs with minor amounts, probably less than 100 t, from the 4,000 t used for feedstock. There is a potential further gain of 10% to the present ozone layer recovery if these emissions were to be eliminated.

MB emissions to the atmosphere from known usage of MB have remained relatively stable since the last Assessment in 2017. MBTOC estimates that a large proportion of the MB used for QPS applications is emitted (83% on average, with wide variation between different applications) and this is released directly to the atmosphere. The remainder of applied MB is converted to non-volatile reaction products and retained in the treated materials and associated packing and structures.

The reduction of emissions of MB to the atmosphere to date has been due mostly to adherence in most cases to phase out schedules under the Montreal Protocol under Annex E for non A5 Parties by 2005 and A5 parties by 2015, and almost complete reductions for MB use presently being requested under the Critical Use exemption process.

There has been an unexplained rise in MB mole fraction in the atmosphere to above 6.0 ppt in mid-2020, one of three small fluctuations observed since 1998. These small fluctuations do not correspond fully with variation in the reported annual global MB production and consumption and the resultant emissions. From 2013 to 2015 there appeared to have been a rise in emissions of MB, equivalent to about 5000 t emissions, followed by a similar magnitude fall in 2015 to 2017. Some studies report that the unexplained part of the gap in the top down to bottom up estimate of emissions may be due to climate impacts and La Nina events. Others have reported that anthropogenic emissions of MB may not be being fully reported or sources fully known from some regions globally. A recent review of the global budget of sources and sinks of MB (both natural and anthropogenic) concluded that the fact that the budget gap declined during phase-out as anthropogenic emissions decline, suggests that at least part of the gap results from underestimation of past anthropogenic emissions. The complete reasons however have not been identified, but this does indicate that potentially there is some MB consumption which is unreported or that emissions of MB may be coming from unidentified sources or greater than anticipated from some current uses.

Uses of MB for fumigation are currently restricted to QPS and a much lesser amount for CUE treatments. Both are exempt from control under the control measures of Annex E. There is opportunity on a technical basis, to control the remaining emissions of MB from fumigations either by adopting recapture/destruction technologies for current QPS structural and commodity fumigations or by adopting non-ODS alternatives. MBTOC estimates that in 2021, 7955 tonnes of MB were emitted from QPS commodity treatments, with about 4296 t available in practice for recapture/destruction. The balance of applied MB that is unavailable for recapture is either lost through reaction to non-ODS degradation products (c.15%) or inadvertently leaked to the atmosphere during and after the fumigation treatment.

Emissions of MB from remaining CUE and QPS soil treatments are considered to be around 500 t, however they are unsuitable to recapture/destruction technologies. It is not known whether they are using barrier films to reduce emissions, but MBTOC considers that this should be mandatory. MBTOC also notes that emissions from these applications could be avoided by adoption of alternative non-MB treatments.

MBTOC notes that a number of Decisions urge Parties to minimise emissions of MB and to use MB recovery and recycling technology where technically or economically feasible for QPS treatments until alternatives to MB are available e.g. (Decisions VII/5, XI/13). In response to this, some countries and local jurisdictions have regulations in place, or proposed, to minimise MB emissions from fumigation operations through use of recapture and/or destruction technologies. Only a few of these regulations are directly targeted at reducing emissions of MB as an ozone-depleting substance. Most relate to ensuring good local air quality and that permitted environmental and workspace MB concentration limits are not exceeded.

A variety of recapture/destruction systems for space fumigations (commodity and structures) are available commercially or at an advanced stage of development. In 2021, total recapture of MB from fumigations is considered to unlikely to have exceeded 100t annually. Quantities of MB recaptured or destroyed are not routinely reportable unless by an Approved Destruction Process.

Reduction in emissions for all remaining uses of MB for QPS, together with identification and stopping any unreported uses are considered important factors to return MB concentrations in the atmosphere to natural levels. Owing to the relatively short lifetime of MB in the atmosphere (0.7 years), adoption of any suitable alternatives and in some cases adoption of recapture/destruction would have an immediate benefit in reducing atmospheric MB levels. It is an important opportunity available to Parties to rapidly enhance ozone layer recovery, with effects of reducing emissions from QPS observable in the stratosphere within 2 years.

This Chapter, as with the past Assessment Reports, continues to refine the best estimate of the level of emissions from current (2021) uses of MB, the most recent year for which good data on MB consumption and use is available. It also provides a summary of the impact of regulation of these emissions on the ozone layer, with updates on developments and potential for reducing emissions of MB through recapture, recycling and destruction for QPS and CUE commodity and structural treatments.

4.2 Atmospheric Methyl Bromide Emissions

4.2.1. Global Sources and Emissions

MB has both natural and anthropogenic sources, the latter contributing about 38% of the global MB emissions at its peak in 1998. Over the last 20 years or so, the basic understanding of the global annual budget (sources and sinks) for MB has not changed significantly (Table 4.1, Figure 4.1). The present understanding of the global MB budget is not balanced although the unknown sources have reduced by about 50% by 2022 (Salzman *et al*., 2022). This imbalance has persisted from pre-Montreal Protocol phase-out (1995-1998) to recent times, Assuming the MB sink estimates are robust, this suggests that natural and/or anthropogenic MB emissions are underestimated in the UNEP/WMO scenarios reported globally (Fig. 4-3).

The natural sources of MB are dominated by the oceans (about 30 k tonnes per year) and terrestrial plants (about 10 k tonnes per year). The MB sinks include chemical losses in the atmosphere (about 60 k tonnes per year), loss to the ocean and to soils (each about 30 k tonnes per year).

Historically, the largest anthropogenic source of MB emission was from fumigation of soils, commodities and structures, where about 68 k tonnes of consumption per year resulted in about 50 k tonnes emitted to the atmosphere between 1995 to 1998 from non-QPS MB use (85%: largely soil fumigation) and commodity and structural uses (15%: largely grain and wood products fumigation, including QPS).

Today, the largest anthropogenically influenced MB source is biomass burning in agriculture, estimated at approximately 25 k tonnes in reports over the last 20 years. This anthropogenic source of MB from biomass burning has existed for a long time and it is difficult to determine the fraction of this emission to be included in the present natural baseline calculations.

Based on atmospheric observations, overall total (natural and anthropogenic) MB emissions have declined from about 175 k tonnes per year in 1995-1998 to about 125 k tonnes in 2017-2020, a fall of 50 k tonnes, consistent with the declining consumption of non-QPS MB with progress in phaseout (Table 4-1, Fig. 4-1).

Emissions of MB to the atmosphere from current uses in 2021 could be reduced by up to 8,500 tonnes if alternatives to MB for QPS uses could be adopted. The impact of the relatively recent and currently limited MB recapture on the global MB budget is presently estimated by MBTOC to be only small (less than 100 tonnes recaptured globally in 2021 (MBTOC estimate).

Survey information supplied under Decision XXIX/4 (TEAP, 2018a) has indicated substantial destruction of MB from time to time. Data are incomplete, but cumulatively, between 1996 and 2016, about 940 tonne of MB destruction was reported by six Parties[7]. In addition, in 2010 TEAP noted that the United States had destroyed 10,500 tonnes of MB between 1996 and 2003 by unspecified processes, likely to be rotary kiln and conventional incineration (see TEAP, 2018a). These quantities of MB destroyed appear to be from industrial processes, e.g. terephthalic acid manufacture, and surplus MB stocks, not from fumigation of soils, structures and commodities.

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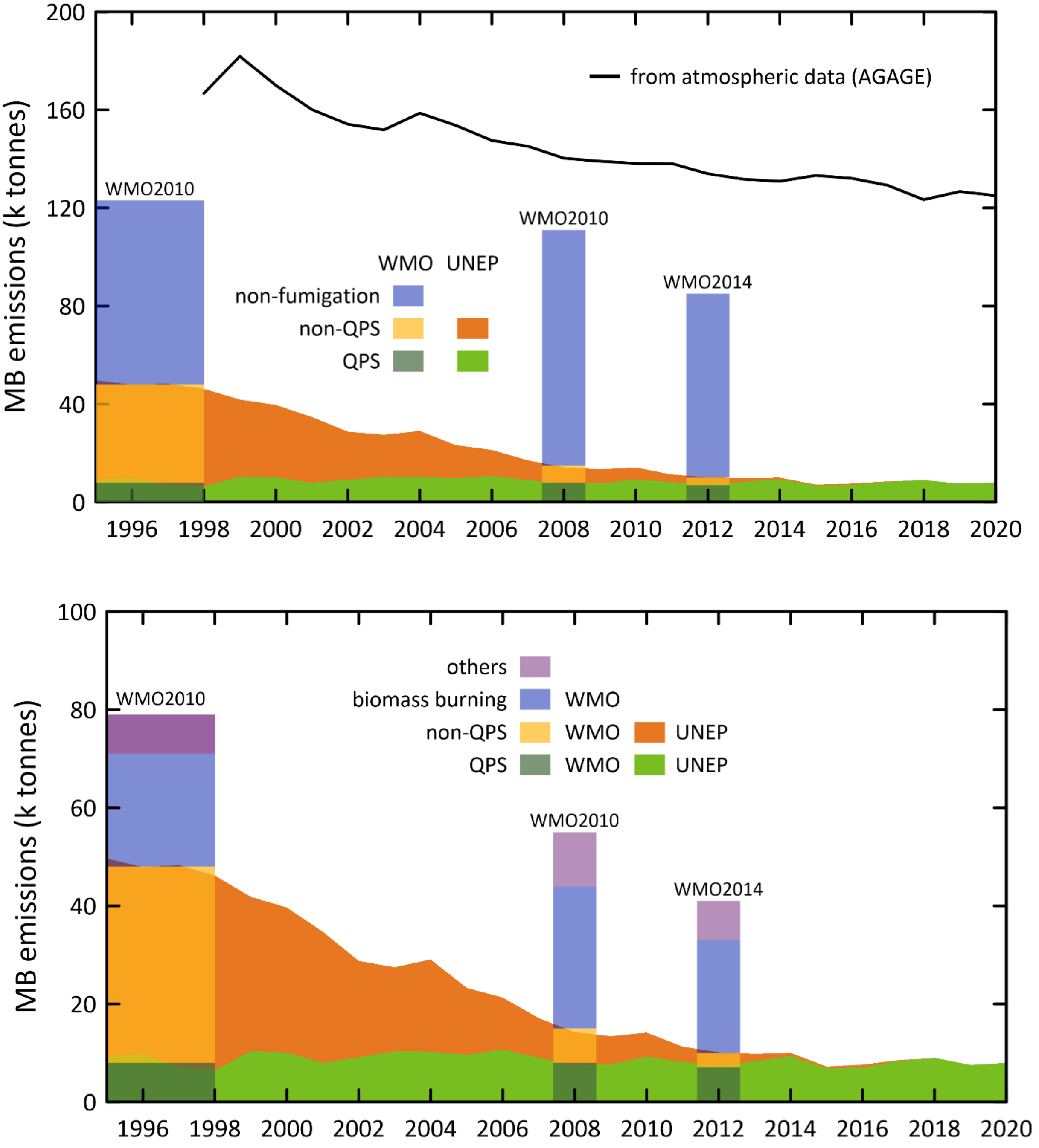
[7] Brazil, Czech Republic, France, Germany, The former Yugoslav Republic of Macedonia, United States of America

FIG. 4-1. TOTAL (TOP) AND ANTHROPOGENIC (BOTTOM) GLOBAL MB EMISSIONS.



As reported in WMO 2010 and 2014 (Montzka and Reimann, 2011; Anon, 2014) and as derived from UNEP consumption data (http://ozone.unep.org/Data_ Reporting/Data_Access/, see text below) and a fumigation emissions model (UNEP: Montzka and Reimann, 2011). Current non-fumigation sources are largely oceans (40%), biomass burning (25%) and vegetation (20%). (Updated data supplied by Paul Fraser and Nada Derek, CSIRO, Australia, 2022)

4.3. Summary of impact of Montreal Protocol control measures and other regulations on the global MB emissions

By 2017-2020, the MB phase-out has led to about a 30% fall in MB (a fall of about 70% of anthropogenic MB) in the troposphere from the late-1990s to 2018 as measured at Cape Grim, Tasmania, Australia (Fig. 4-2). Owing to the short atmospheric lifetime of MB (half-life, 0.7 years), changes in emissions of MB at ground level are rapidly reflected in changes in tropospheric and stratospheric MB concentrations. This is in contrast to almost all other ODSs regulated under the Protocol, as all (except methyl chloroform) have much longer atmospheric lifetimes.

In 2003, it was predicted that MB levels in the Southern Hemisphere would fall to about 7 ppt before levelling off (Fig. 4-3, A1 WMO, 2003). However, by 2015 the levels had continued to fall close to 6 ppt, lower than anticipated by more recent scenario modelling (Fig 4-2 and 4-3, WMO 2011, WMO 2015). It is clear that the Montreal Protocol restrictions on the use of MB are having greater impact on atmospheric MB levels than thought possible 10 years previously and this has been supported by more recent scientific observations (Salzman *et al.*, 2022).

In 2010, it was reported (Porter *et al.* 2010) that prior to the onset of the widespread use of MB as a soil and structural fumigant in the 1960s, the historical background or baseline concentration of MB in the stratosphere prior to the 1940's was around 5.4 ppt (Figures 4-2 and 4-3, southern hemisphere values). The concentration then grew rapidly through the 1970s to the late 1990s due to large anthropogenic (man-made) use of MB (up to 72 k tonnes annually). In the mid-1990s the concentration reached 8-9 ppt (more than 60% above the 1940s natural baseline concentrations) but started falling in the late-1990s as a result of the MB reduction for controlled uses imposed by the Montreal Protocol.

The rate of decline in the MB concentration in the atmosphere has been relatively constant and MB concentrations have fallen to less than 6 ppt as measured in 2018-2021 (Figs. 4-2 and 4-3). Since 2016, there has been an apparent flattening of the fall in concentration of MB in the troposphere and a small rise in concentration from 2018 onwards. This may be partly related to an increase in consumption for QPS from 8.3 k tonnes in 2015 to 10.1 k tonnes in 2017 and onwards, but potentially is also due to unreported or inaccurately reported consumption data under Article 7 reporting (Choi *et al.*, 2022). There may also be some impact of La Nina climatic conditions affecting atmospheric concentrations of MB (Salzman *et al.,* 2022).

A recent review of the global budget of sources and sinks of MB (both natural and anthropogenic) concluded that the fact that the budget gap declined during phase-out as anthropogenic emissions decline, suggests that at least part of the gap results from underestimation of past anthropogenic emissions (Salzman *et al.,* 2022). The complete reasons however have not been identified, but this does indicate that potentially there is some MB consumption which is unreported or that emissions of MB may be coming from unidentified sources or greater than anticipated from some current uses. The likelihood of major bushfires increasing yearly levels of MB in the atmosphere seem to have been discounted as these appear to mainly affect variation over the year not between years (Nicewonger *et al.,* 2022).

Data suggests that further decline MB emissions will only occur if emissions from use of MB for QPS are reduced significantly. In 2021, the use and emissions of MB for QPS sources was more than fifty times the total reportedly used for non-QPS (CUE) in non-A5 and A5 countries.

TABLE 4 -1. ESTIMATED GLOBAL MB SOURCES (EMISSIONS) AND SINKS (K TONNES): 1996-1998, 2008, 2012

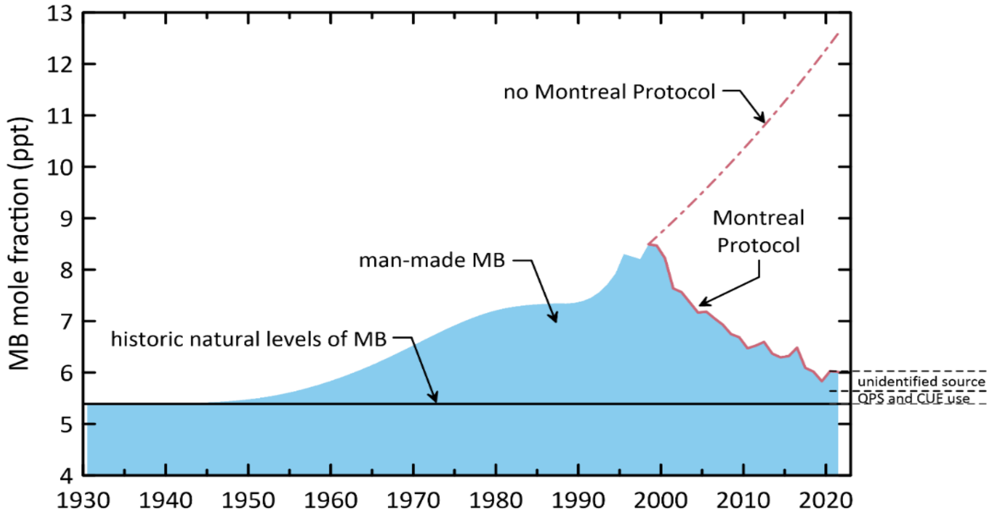
Sources	1995-1998[a]	2008[b]	2012[a]	Comments
Anthropogenic	**80**	**56**	**41**	
fumigation: non-QPS	40	7	3	only source controlled by MP
fumigation: QPS	8	8	7	exempted from control under MP
biomass burning	23	29	23	open-field, biofuels
rapeseed	5	5	5	
leaded petroleum	3	<6	<3	
rice agriculture	<1	<1	<1	
Natural	**43**	**54**	**44**	
oceans	32	42	32	
salt marsh	7	7	7	
plants	2	2	2	mangroves, shrubs
fungus	2	2	2	
wetlands	<1	<1	<1	largely peatlands
Total Sources	**123**	**111**	**85**	

Yvon-Lewis et al., 2009; Montzka et al., 2011; Anon, 2014

Sinks	1995-1998[a]	2008[b]	2012[a]	Comments
oceans	-41	-49	-30	
atmosphere	-81	-67	-60	oxidation, photolysis
soils	-40	-32	-27	
Total sinks	**-162**	**-148**	**-117**	

[a]Carpenter and Reimann, 2014; [b]Montzka and Reimann, 2011

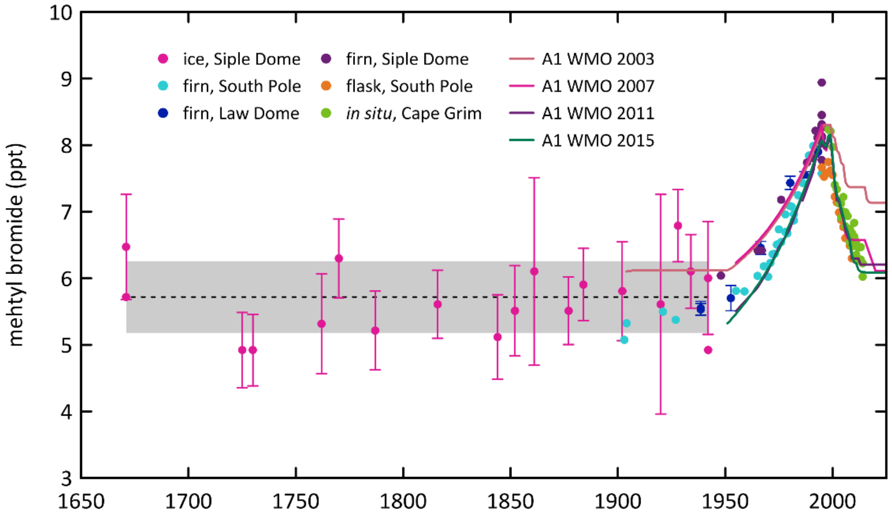
FIG. 4-2. THE IMPACT OF MB RESTRICTIONS IN NON-QPS USES ON MB CONCENTRATIONS IN THE TROPOSPHERE OF THE SOUTHERN HEMISPHERE SINCE THE LATE-1990S (RED LINE).



Updated by Paul Fraser and Nada Derek, CSIRO, Australia, 2022

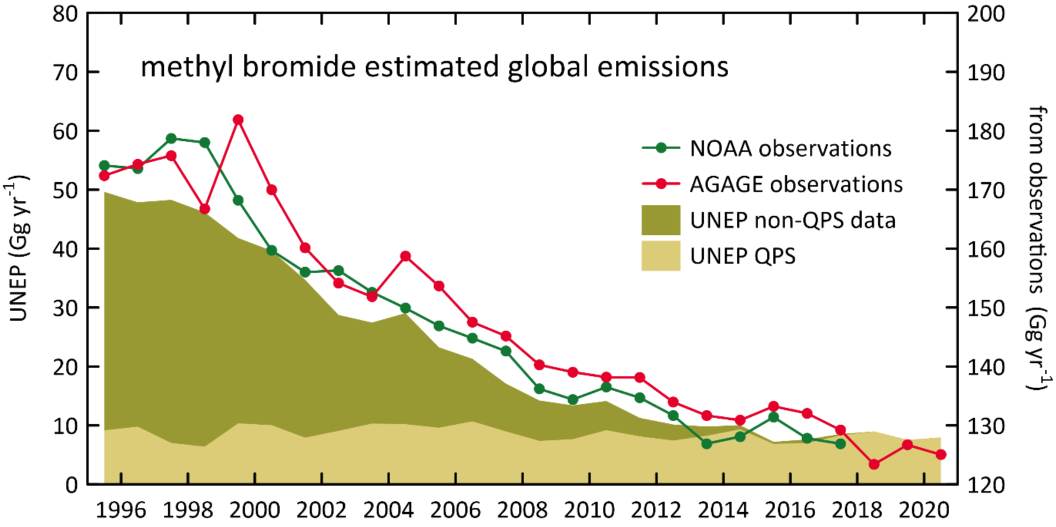
The fall in MB mole fraction shown in Fig 4.2 represents around a 40 k tonne reduction of emissions (see Fig 4.4). The *solid line* in Fig 4.2 indicates the level of MB from natural sources (i.e. the historic baseline), which is assumed to be constant in time. Current MB levels are about 1.0 ppt above natural levels of MB. About 40% of this is from remaining QPS and CUE MB uses, the other 60% from unidentified sources. The possible scenario shown in Fig 4.2 without the regulations of the Montreal Protocol is estimated from past trends (Montzka and Fraser, 2003; Clerbaux and Cunnold, 2007; Daniel and Velders, 2007).

Fig. 4-3: Historic MB levels (ppt = parts per 1012 molar) in the Southern Hemisphere over the past 350 years



Data are from Cape Grim, Tasmania (CSIRO unpublished data), and various atmospheric and ice/firn sampling sites in Antarctica compared to modelled MB levels (WMO 2003, WMO 2007, WMO 2011, WMO 2015) as reported in the past four Scientific Assessments of Ozone Depletion (SAP, https:/ozone.unep.org).

Fig. 4-4: Reported annual anthropogenic* (QPS + non-QPS) MB emissions (UNEP data) compared and fitted to total (from atmospheric data) annual global observations of MB



* Anthropogenic data (left axis) is from a simple emissions model, based on reported UNEP global QPS and non-QPS consumption data (Figure 1-8 in Montzka *et al*., 2011); (ii) total (man-made + natural) emissions (right axis) from atmospheric observations and a 1-box model (NOAA: green) and a 12-box model (AGAGE: red), (Montzka and Reimann, 2011; S. A. Montzka, NOAA, unpublished data; AGAGE unpublished data). The estimated annual MB emissions from QPS since 2009 are ~ 8 Gg (8 k tonnes), Table 4.1). (Updated data supplied by Paul Fraser and Nada Derek, CSIRO, Australia, 2022)

4.4 Impact of higher production levels of MB than reported consumption on emissions

During the period 2006 to 2013, there was over 6-8,000 t of MB production that was not shown in subsequent consumption. This is reflected in a period of higher emissions during the period from 2006 to 2014 than would be predicted from bottom up estimates of consumption (Figure 4.4). Whilst a portion of these quantities may have been stored as stocks, the emissions have always stayed higher than anticipated, leading to roughly twice as much emission from anthropogenic uses in the atmosphere at present compared to what is expected to be, above the estimated global baseline in the atmosphere from reported consumption of QPS and non QPS uses.

4.5. MB emissions from current uses for soil, commodities and structures

4.5.1 Current levels of consumption of methyl bromide for fumigation

As at 1 January 2022, remaining uses of MB for fumigation are restricted to Critical Use Exemptions (CUEs) or Quarantine and Pre-shipment uses (QPS). In 2021 these categories consumed 80 tonnes and 10,143 tonnes of MB respectively (see Table 4-3, below).

Other uses of MB for fumigation are now phased out under control measures of Annex E of the Montreal Protocol in both A5 and non-A5 countries.

Only part of the MB dosage applied in fumigations is lost or intentionally discharged to atmosphere. A portion of applied MB is lost by reaction to give non-volatile breakdown products.

4.5.2 Decisions of the Parties urging restriction of emissions of methyl bromide from fumigations

There are several Decisions urge Parties to minimise emissions of MB to the extent possible in situations where they still use MB and are unable to adopt non-ozone depleting alternatives.

Parties have been urged to minimise MB emissions from fumigations for uses considered for CUEs in Dec IX/6 (1,b,(i)) and to adopt recovery and recycling technology to reduce emissions of MB for QPS treatments where technically and economically feasible and in the absence of non-ozone depleting alternatives (Decisions VII/5(c), XI/13(7)).

In relation to QPS fumigations with MB, Decision XX1/10 (4) states:

“To encourage parties to apply best-practice measures to reduce MB quarantine and pre-shipment use and emissions, that may include the review of required use dosages, gas tightness controls, monitoring during fumigation and other measures to minimize MB dosages, and, in applications where alternatives are not yet available, the recovery and possible reuse of MB, and to review the MB quarantine and pre-shipment requirements for possibilities of introducing alternative mitigation measures whenever possible;”

4.5.3 Potential sources of MB emissions from MB fumigation applications.

During any use of MB before, during and after a fumigation operation, there are five distinct sources or opportunities for MB to be emitted to the atmosphere. These are summarised in Table 4.2, together with some measures that can be applied to mitigate these emissions. These measures are consistent with those given in Decision XXI/10 (7).

In general, the main losses in a typical fumigation occur during the fumigation exposure period from unintentional leakage and then subsequently during the intentional venting (airing off) phase. In practice, quantities and proportions of MB lost to atmosphere vary widely between the kinds of fumigation (soil treatments, commodity and structural fumigations), environmental factors (e.g. temperatures, wind) and quantities and types of material treated.

Use of recapture and/or destruction in place of intentional venting of residual MB to atmosphere is discussed in Section 4.5.4, below.

TABLE 4-2: ESTIMATED % LOSSES OF MB FROM FUMIGATION TREATMENTS AND TECHNIQUES TO MINIMISE THE EMISSION LOSSES

Stage of methyl bromide pathway	Techniques to Minimize Emissions	% of applied dosage emitted under best practice (MBTOC estimates)
Inadvertent emissions during manufacture, leakage during handling and transport and emissions during decanting. Cylinder handling after discharge in fumigation (residual MB in cylinder)	Good process design. Training of staff.	<2%
Unintentional discharge of some unreacted MB during applications when changing cylinders, lifting rigs from soil to reverse direction, etc.	Training and good process control	<0.5%
Leakage during the fumigation enclosure during the exposure period.	Good sealing of the fumigation enclosure (commodity, structural treatments), good sealing of edges and joins of sheeting (soil treatments), low permeability of sheeting to MB, avoiding treatments under windy conditions. Appropriate dosage, reduced need for top-up.	3 - 20%
During venting or discharge of unreacted MB after completion of fumigation after the set exposure period.	Use recapture technology. Reuse recaptured MB.	40 – 95%
Following treatment when the treated soil, commodity or structure emits some sorbed, unreacted MB, often over an extended period of time.	Extend exposure period (containment) if possible to allow more MB to react to give non-volatile reaction products	0.5 – 5 %

4.5.4. Quantities of methyl bromide lost to atmosphere from various types of fumigation

In practice, the rate MB is lost to atmosphere varies widely between the kinds of fumigation (soil treatments, commodity and structural fumigations), the level of sealing achieved, environmental factors (e.g, temperatures, wind) and quantities and types of material treated.

Effective retention of fumigant around the treated commodity or soil allows most efficient use of the fumigant. It also ensures maximum time for reaction of the MB with materials within the fumigation enclosure. During fumigation some of the gas becomes sorbed on the treated materials or the packaging/palleting in commodity treatments or into the soil for preplant treatments. Some of the sorbed MB remains unchanged and will air off at the end of the treatment, but a portion of the sorbed MB is converted into non-volatile residues.

In soil treatments, degradation is due to reaction with soil organic matter and some mineral constituents as well as other reaction pathways such as hydrolysis (De Heer *et al.,* 1983; Dungan and Yates, 2003). In commodity fumigations, degradation is through reaction of the MB with active N, O and S atoms in the foodstuff, timber or other treated commodity and associated materials, producing methylated products (Winteringham *et al.,* 1955) and bromide ion. In both cases the quantity of MB potentially released to atmosphere is thus reduced by the quantity reacted and converted to non-volatile breakdown products.

Table 4-3 provides estimates of emissions from all current uses reported by Parties. At 1 January 2022, uses of MB as a fumigant were restricted to uses exempted from the control measures of the Protocol i.e. CUEs and QPS uses.

The overall usage figures given in Table 4-3 are derived from a combination of reported 2021 global consumption for QPS in major Article 5 and non A5 countries. The usage figures for the individual sectors are based on tonnages estimated from these data sources and voluntary surveys provided to MBTOC by major MB user countries in 2022. Under current usage patterns, the proportions of applied MB eventually emitted to the atmosphere are estimated by MBTOC to be 46 - 91%, 85 - 98%, 51 - 98% and 85 - 98% of applied dosage for current uses for soil, perishable commodities, durable commodities and structural treatments respectively. These figures, weighted for proportion of use and particular treatments, correspond to a range of 46 - 98% overall emissions of MB from agricultural and related uses, with a mean estimate of overall emissions of 83%.

Best estimates of annual MB emissions from all sources of fumigation use in 2021 are 8,508 tonnes (Table 4.3) and are marginally lower than in 2017 which totalled 8,544 tonnes. During this period there have only been minor reductions in usage for soil fumigation for controlled uses, counterbalanced principally by increases in fumigation of timber and wood packaging materials treated to meet Quarantine and Pre-shipment requirements. The total reported QPS consumption under Article 7 has varied from 8,174 tonnes in reported in 2015 to 10,223 tonnes in 2021 (see Fig4.3.)

TABLE 4-3: ESTIMATED GLOBAL USAGE OF MB AND EMISSIONS TO ATMOSPHERE IN 2021 FOR MAJOR USE CATEGORY, INCLUDING QPS.

Type of fumigation and commodity/use	**Estimated usage (a)**		**Estimated emissions**	
	tonnes	%	tonnes	% (*b*)
CUE (Non QPS)				
Preplant soil fumigation	35	0.4	32	69 (46-91)
Structures, commodities and perishables	45	0.05	41	92 (85-98)
Sub Total- non QPS	***80***	***1***	***73***	***81***
QPS				
Preplant soil fumigation *(c)*	800	9	480	69 (46-91)
Timber and wooden packaging	6180	61	5442	88
Durables and miscellaneous (timber/grains)	2307	23	1730	75 (51-98)
Perishables	856	8.4	783	92 (85-98)
Sub Total- QPS	***10143***	***99***	***8435***	***84***
Total estimated fumigant use	**10223**	**100**		**71- 91**
Best estimate over all categories			**8508**	83

(a) Estimated usage based on QPS consumption data (in this Assessment), authorised CUE use for 2021 and MBTOC survey of non A5 or Article 5(1) consumption and use, excluding feedstock. Reported use of stocks included. No allowance for unreported use. *(b)* For original sources of estimates, see MBTOC 1995 with minor subsequent adjustments. *(c)* Use of VIF or TIF assumed.

There has been a slow increase in the calculated best estimate of % emissions since 1984 (Table 4.4). The trend towards use of increasingly emissive uses reflects the now dominant use of MB for QPS purposes and phaseout of lower proportional emissions from soil fumigations under impermeable sheeting. This estimate gives a upper limit to the amount of MB that is recapturable or otherwise controllable.

The estimate of total emissions MB (Table 4.4) has fallen with progress in phaseout of non-exempt controlled uses.

TABLE 4-4: CHANGES IN TOTAL ESTIMATED FUMIGANT USE AND BEST ESTIMATE OF ATMOSPHERIC EMISSIONS OVER ALL MBTOC ASSESSMENTS.

Total estimated MB use	Year	Best estimate of emissions (tonnes)	Best estimate of % of applied MB emitted	Assessment Report Reference
10223	2021	8508	83	This Assessment
10481	2017	8544	82	MBTOC (2018)
11306	2013	8781	77	MBTOC (2014)
22060	2009	17041	75	MBTOC (2010)
36866	2005	27601	75	MBTOC (2006)
56299	2001	41317	73	MBTOC (2002)
68666	1997	50126	73	MBTOC (1998)
76063	1993	48680	64	MBTOC (1995)

4.6. Emission Reduction through Better Containment, Recapture or Destruction.

4.6.1 Introduction

At this time (December 2022), almost all MB fumigations (>99% by consumption) are categorised as for QPS purposes.

Emission reduction is aimed, with regard to the Protocol, at reducing the quantities of methyl bromide emitted from fumigation treatments. Emission reduction (minimisation) may be achieved by:

i. A high level of containment (sealing of the fumigation enclosure and associated dosage minimisation)
ii. Minimisation of quantity of MB needed to achieve satisfactory fumigation performance, and
iii. Recovery of residual MB at end of fumigation, with destruction or reclamation for reuse.

In the past, combinations of MB with other active chemicals have resulted in lowered use of MB compared with use of MB alone (e.g. use of MB/pic in place of 100 or 98%MB in soil fumigations). This transitional approach could theoretically be used for QPS commodity and structural treatments.

Some regulatory practices aimed at reducing excessive use of MB in soil fumigation are described in MBTOC (2018).

Reduction of emissions of MB in intentional discharge (venting) can be achieved by recapture followed by recycling, reclamation or destruction or by direct destruction. For most commodity and structural fumigation operations, intentional venting following fumigation results in the largest component of total discharge (emission) to atmosphere (Table 4.2). Theoretically, this MB is available for recapture and reuse or destruction, although there are several operational factors that lead to reduced recapture efficiencies.

This section discusses in detail only recapture and destruction technologies designed for use with commodity and structural QPS fumigations. QPS post-harvest disinfestations of commodities and structures using MB are performed, or should be performed, under well sealed conditions that limit loss of the fumigant to atmosphere during the exposure period. A high standard of effectiveness is required for QPS and particularly Quarantine (biosecurity) treatments. Consequently, they tend to be strictly regulated worldwide. Good containment is a prerequisite for efficient use of recapture/destruction.

Some attempts have been made to apply recapture to soil fumigations, but the geometry and situation of soil fumigations render this problematic. Experimental recapture/destruction systems include adding thiosulphate reactant through driplines below the plastic soil cover, use of carbon-containing cover sheets, and vacuum extraction from below sheeting into absorbent. No full-scale technologies for soil fumigations, to knowledge of MBTOC, are in current use.

4.6.2. Legislation and regulations relating to use of recapture/destruction of methyl bromide from fumigations.

Approved destruction process. One process involving thermal decay of MB from dilute airborne sources of MB was recently approved as a Destruction Process under Decision XXIX/4 (TEAP 2018b). The technology is based on destruction of MB by thermal decay in a single pass destruction step, followed by conversion of the by-products through a water-based scrubbing system. The TEAP Destruction Taskforce determined that the DRE was >99.99%, and exhaust concentrations of HBr, CO and particulate emissions met the required performance criteria.

An embodiment of this principle for large scale use, combustion of fumigant in air in a modified diesel engine, is at an advanced stage of development (K. Bartolo, Mebrom Pty Ltd, pers. com. 2022).

State regulations mandating recapture and destruction. Most legislation requiring recapture/destruction of MB from fumigations has been aimed at ensuring that local environmental and workspace air quality standards are met. It is not specifically targeted at ozone-layer protection. There have been a few exceptions. Examples include:

1. Regulation under the Environmental Protection Act of Victoria, Australia (Anon. 2001)
2. Restrictions on MB use as part of EU phaseout of MB (including for QPS purposes) (MBTOC 2008).

As examples, carbon -based scrubbing (recapture) systems have been fitted to fumigation chambers treating fresh fruit and vegetables in a wholesale market in Melbourne, Victoria, Australia in compliance with the Victorian Act. Two carbon-based recapture technologies were deployed as transitional measures during the phaseout of MB fumigation in Belgium.

Environmental regulations requiring recapture from log fumigations are examples of requirements for recapture for local air quality protection, not directly for ozone layer protection. Examples include:

1. Recapture under development for log fumigation in New Zealand (MPI 2021)
2. Recapture to be fitted to North Carolina log fumigations (WUNC 2018)

In neither case are there any recapture/destruction fitted and in routine use yet. Performance trials have been carried out with two candidate systems for recapture and destruction for log fumigations in New Zealand (MPI 2021)

4.6.3 Destruction of methyl bromide reported under Article 7 and elsewhere.

TEAP (2018a) summarised progress on development and historical deployment of destruction technologies to 2017. At that time there were currently no approved Destruction Technologies for MB However, MB destruction had been reported to the Ozone Secretariat under Article 7 data reporting. Cumulatively, between 1996 and 2016, 938 tonnes of MB destruction were reported by six Parties, and with destroyed quantities being reported, by one or more Parties, each year since 2005.

In addition, the 2010 TEAP Progress Report Volume 2 noted that the United States had destroyed 10,531 tonnes of MB between 1996 and 2003 (quoted in TEAP, 2018a). Furthermore, the 2016 Toxics Release Inventory showed a total of 112.6 tonnes of MB released as fugitive and stack releases in the United States, with 1,499.8 tonnes destroyed on-site in the category 'Chemical Industry', with none reported from the 'Food' sector. In 1994, the Food sector had reported venting of 209 tonnes, while the Chemical Industry vented 1006 tonnes, recycled 350 tonnes and destroyed 85 tonnes. Details of the recycling and destruction processes were not given. GIZ, the German Technical Cooperation Agency has funded MB destruction projects in Sudan to dispose of over eight tonnes of old stocks of MB (EEA, 2016).

There has been no recent reporting of MB destruction under Article 7.

Informal data available to MBTOC indicates that quantities of MB not emitted to atmosphere as a result of recapture and destruction from fumigations was unlikely to exceed 100 tonnes in 2021. a small proportion of total MB fumigant usage.

4.6.4. Bulk methyl bromide destruction technologies

For the destruction of bulk MB, a United States' submission (quoted in TEAP 2018a) stated that two commercial destruction facilities destroyed MB in the 2010 to 2016 period using:

- Gas/Fume Oxidation (normal thermal destruction)
- Rotary Kiln Incineration

In addition to those facilities that destroy ODS commercially, some companies destroyed MB on-site from 2010 to 2016, either as a by-product of manufacture or when it is used as raw material in a manufacturing process.

Destruction by hydrolysis has been used to destroy surplus and outdated stocks of liquid MB fumigant as supplied, stored in steel cylinders. The process was used to destroy 5 tonnes of surplus MB, using a transportable destruction unit (GIZ (2012); Remondis, 2022)

4.6.5. Scope for emission reduction by recapture/destruction and practical limitations.

Theoretical maximum recoverable methyl bromide.

The maximum proportion of applied MB recoverable from a fumigation is limited by the irreversible chemical reaction with the contents of the fumigation enclosure – water and chemical components of the fumigated commodity and associated materials. The proportion of added non-volatile bromide residue formed as a result of a treatment is a direct measure of the proportion of the applied MB not emitted to atmosphere, provided an allowance is made for natural or added bromide ion already present prior to treatment.

Only the remaining MB is potentially available for recapture and/or destruction. In practice there are inadvertent losses of fumigant during the fumigation exposure period that further reduce quantities available for recapture (see below). For maximum 'recapturable' MB from a fumigation, leakage from the system must be minimised. This is common good practice for QPS fumigations.

The maximum potential for recovery from enclosed space fumigation and soil treatments, can be estimated from the total emissions expected. Estimated emissions and ranges for various categories of fumigation, including soil, commodity and structural QPS fumigations, are given in Table 4.3.

Applied fumigant available for recovery – practical limitations.

In practice, there are several factors that limit the proportion of unreacted MB fumigant that can be displaced or extracted from fumigations. These limitations substantially reduce the actual 'recapturable' MB in routine use.

Principal limitations leading to reduced capture of applied fumigant:

- Reaction with enclosure contents to give non-volatile products
- Leakage from the enclosure during the exposure period
- Slow desorption of intact fumigant from treated commodity and associated packaging
- Breakthrough from absorption beds (if used), incomplete reaction with scrubbing solutions (if used)

Reaction with enclosure contents to give non-volatile products. Reaction with enclosure contents has already been allowed for in calculations for maximum attainable efficiency of recapture/destruction (Table 4-2). It is not easily controllable in normal fumigation situations.

Leakage from the enclosure during the exposure period Leakage is controlled in normal good fumigation practice and particularly so with QPS commodity and structural fumigation where a high level of reliability and effectiveness is required. Even with a good level of sealing of the enclosure, significant inadvertent losses from leakage typically occur. These are much greater with prolonged fumigations such as with 24 h exposures commonly used for QPS grain fumigations in silo bins and log fumigations under sheets. Together, these were the main users of MB by weight in 2022.

Leakage as a loss factor is further discussed in MBTOC (2018). As an example the recently revised standard, ISPM 15, for fumigation of wood packaging material specifies the following minimum retention rates for MB fumigant (Table 4.5). Leakage and sorption result in substantial losses from the gas phase. The specified minimum retention is 50% of initial specified dosage in the gas phase after 24 h, with the losses resulting from a combination of leakage and sorption on the fumigated materials (some reversible, some irreversible).

TABLE 4-5: ISPM 15 STANDARD FOR TREATMENT OF SOLID WOOD PACKAGING MATERIAL. METHYL BROMIDE DOSAGE RATES AND CONCENTRATIONS AT 24H EXPOSURE. (IPPC 2019).

Temperature	Dosage (g/m^3)	Minimum concentration (g/m^3) at 24h:	% retention at 24 h
21°C or above	48	24	50
16 - 20.9°C	56	28	50
10 - 15.9°C	64	32	50

Slow desorption of intact fumigant from treated commodity and associated packaging. Some commodities desorb intact MB fumigant slowly after long fumigations (e.g. 24 h exposures or at low temperatures (e.g. <15°C). Measurable quantities of MB continue to be released over several days after the start of airing off (venting) of the fumigant. Running of recapture and destruction equipment when the MB concentration extracted from the fumigation enclosure has fallen to low levels becomes inefficient and uneconomic with regard to ozone-layer protection. However, it may be a requirement for recapture units operated to ensure local air quality is not hazardous to workers and bystanders.

Breakthrough from absorption beds (if used), incomplete reaction with scrubbing solutions (if used). With correct sizing, design and operation, most absorption and scrubbing systems can remove almost all fumigant presented to the system. In practice, absorption systems are run until there is measurable breakthrough of fumigant from the absorption bed, with resulting inefficiencies.

TEAP (2002) estimated that 70% of applied material could be recovered from QPS and other fumigations of structures and commodities in 2002. With commodity and structural fumigations are now limited (or should be) to well-conducted QPS, this estimate needs to be reconsidered, taking into account considerations above and quantities of total MB for different applications (Table 4.2). The actual figure achievable in practice in individual situations will vary substantially from this estimate according to the particular circumstance.

In general, shorter fumigation times give less time for sorption into treated products, less time for inadvertent leakage and less time for reaction to destroy part of the added fumigant. Thus it can be expected that there is a higher fraction of recoverable fumigant in a 2 h duration fumigation of perishables than a 24 h fumigation of grain or timber. As an approximation, the concentration of fumigant left at the end of well-conducted treatments represents 100% of easily recoverable and 'recapturable' fumigant.

Table 4.6 gives an estimate of 'recapturable' MB in aggregate and by current category of QPS commodity use. This assumes that recapture is only feasible in practice for QPS commodity treatments. The estimates of the fraction of initial dosage remaining after required exposure time is taken from ISPM15 (Table 4.5 above) for 24 h fumigations of wooden packaging material, and Department of Agriculture and Water Resources (Australia) specifications (DAWR, 2018) for 2 h exposures of perishables and 24 h exposures of grains and similar commodities.

With these assumptions, it is estimated that it would have been possible to recapture or destroy about 4300 tonnes (43%) of the 2021 total consumption of 10143 tonnes MB.

TABLE 4-6. ESTIMATES OF RECAPTURABLE METHYL BROMIDE IN PRACTICE FOR QPS COMMODITY FUMIGATIONS (2021 DATA)

Category of QPS use	Typical fumigation period (h)	% Remaining in gas space	Tonnage MB used (2021)	Recapturable tonnes, estimate
Timber and wooden packaging	24	50	6180	3090
Grains and miscellaneous	24	30	2307	692
Perishables	2	60	856	514
Total			**8343**	**4296 (46%)**

4.7. Commercial and developmental processes for MB recapture and destruction from fumigations

Recapture and destruction processes have the potential to reduce MB emissions from a range of commodity fumigation operations, but not soil treatments. At this time, all of these fumigations are QPS treatments, with an estimated emission of 7955 tonnes in 2021 from Table 4.3).

A number of techniques have been proposed or investigated for their potential to recapture MB after fumigation operations. In some cases the recaptured MB is recovered in liquid or gaseous form, but usually the MB is subsequently destroyed or released by further processing after recapture. While versions of many of the approaches given below (Table 4.7) have been in some commercial application, recapture on activated carbon is currently the main system in full scale, commercial use.

TABLE 4-7: PROCESSES FOR RECAPTURE OR DESTRUCTION OF METHYL BROMIDE (DILUTE SOURCES) IN AIR EXTRACTED FROM FUMIGATIONS. PROCESSES IN PILOT OR FULL-SCALE COMMERCIAL USE.

	Primary process	**Subsequent processing**	**Reference - examples**
Physical processes	Condensation with refrigeration or liquid nitrogen	Direct reuse or reuse with reclamation	MBTOC 1995, TEAP 2018a
	Sorption on activated carbon	Desorption by heat with direct reuse of evolved gas, or secondary destruction of evolved MB	Nordiko 2022, TIGG 2022. MBTOC 2014
		Deep burial of loaded carbon	Nordiko 2022
		Chemical destruction of MB in situ by various reactants (e.g. thiosulphate, ozone) with heat regeneration of the carbon bed if necessary.	Value Recovery 2022, MBTOC 1998
	Sorption on methyl bromide-selective zeolite	Heat regeneration of the zeolite with refrigeration condensation of desorbed MB for reuse, storage or destruction.	See MBTOC 1995
Chemical processes	Thermal combustion in air	Combustion exhaust scrubbed to remove HBr and Br_2 products	EIM Technologies 2022
	Catalytic combustion in air		See TEAP 2018a
	Liquid scrubbing with nucleophiles in solution (thiosulphates, ammonia, amines)	Chemical waste disposal of solution containing reaction products	Joyce et al., 2004, MBTOC 2018
	Hydrolysis with alkali		See TEAP 2018a

Comparative performance data for the various recapture/destruction units in full scale operation or at advanced developmental stage is usually unavailable.

One third party study of two potential recapture/destruction processes has been published recently (MPI 2021). The study involved monitoring comparative performance of two competing types of recapture/destruction units under commercial field conditions. These were an activated carbon absorption system (2 units) and a chemical scrubbing unit using a proprietary reactant solution.

Across seven cargo types, including large scale fumigation of pine logs, the average recapture efficiency of the physical recapture systems under the conditions evaluated was ≥88.80%; while the average recapture efficiency of the chemical recapture system was shown to be ≥47.66%. These values represent the percentage of MB recaptured from the air space concentration remaining at the end of the fumigation period.

The study showed that the physical process of sorption on carbon was more rapid than the chemical scrubbing system in the versions of the two units tested. Loaded carbon from the carbon-based sorption system was deep buried off-site, a system cheaper than the alternative washing with reactant and drying for reuse.

4.8. Prospects for adoption of widespread recapture and destruction.

Economics will tend to favour destruction over recycling in situations where new MB continues to be easily and cheaply obtainable for QPS purposes and destruction technologies are relatively cheap, including allowance for disposal of products of the destruction system.

While status of recycled ODS is clarified under the Montreal Protocol in Decision IV/24, the status of recovered or reclaimed MB as regards pesticide registration status remains unclear

There are increasing numbers of installations, based on active carbon systems that are designed to recapture MB after well-contained commodity treatments. These may be designed for capture of fumigant in a broad range of concentrations, including trace levels in the ppm v/v range and below. These units are being attached to MB fumigations in port areas and other urban environments or transport containers containing residual gas to remove fumigant to comply with local regulations for toxic gas emissions, air and environmental quality and worker safety.

Most of the recovery technologies mentioned above are complex in nature. In many cases, they are likely to be a significant part of the total cost of a new fumigation facility or to contribute significant capital cost or hire costs to apparatus associated with mobile treatment units. Most have significant running costs compared with costs of treatments.

Because of the extra costs associated with recapture, it is unlikely there will be substantial adoption for ozone-layer protection without some incentives or regulatory intervention. Adoption in the absence of such measures or other requirements, such as local air quality specifications, will place early adopters at a competitive disadvantage compared with those that chose not to adopt recapture.

The technologies are unlikely to become widely used to assist ozone layer protection without further international and national economic and regulatory drivers, such as those recently imposed in New Zealand. As New Zealand is a major user of QPS MB (5th largest user), technologies implemented there will have global implications.

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5

5. Alternatives to Methyl Bromide for QPS Applications

5.1. Introduction

Article 2H of the Montreal Protocol exempts methyl bromide used for QPS treatments from phase-out for quarantine and pre-shipment purposes. Methyl bromide fumigation is often the preferred treatment for certain types of perishable and durable commodities in trade worldwide, as it has a well-established, successful reputation amongst regulatory authorities to prevent the spread of quarantine pests. MB is used in a variety of QPS treatments as described in section 5.2 and others in this chapter.

Parties to the Montreal Protocol are nevertheless encouraged to minimize and replace MB for QPS whenever possible. In the past, MBTOC has identified opportunity for replacing between 30 and 45% of QPS uses with immediately available alternatives, particularly in the case of pre-shipment uses.

Since the MBTOC 2018 Assessment Report (MBTOC 2019), some parties have made significant technical advances and taken policy decisions leading to reductions and even phase-out of MB for some QPS applications. Such policies are stricter than controls established by the Montreal Protocol and are mainly due to concerns for worker safety. In 2010, the European Union phased out all uses of MB. New Zealand recently implemented a policy of no emissions from all QPS uses of MB and North Carolina in the US has also imposed recapture technologies. MBTOC regularly provides more detailed information on alternatives to MB for QPS uses through its annual TEAP Progress Reports.

Quarantine treatments are generally approved on a pest and product specific basis following bilateral negotiations between interested countries and may require years to complete. This process helps ensure safety against the incursion of harmful pests which could cause enormous losses to local agriculture. For this and other reasons, replacing methyl bromide quarantine treatments can be a complex issue. Many non-methyl bromide treatments are however published in quarantine regulations of many countries and are in use, but these are often not the treatment of choice due to convenience, cost or availability.

Nevertheless, since the 2018 Assessment report there has been increased acceptance under bilateral arrangements and International Plant Protection Convention (IPPC) regulations of a number of technical alternatives are as effective as MB for specific commodities and very significant pests such as fruit flies (see section 5.11).

Global production of methyl bromide for QPS purposes in 2021 was 10,465 tonnes, increasing by about 20% from the previous year. Production occurs in five parties, China, India, Israel, Japan and USA. Although there are substantial variations in reported QPS production and consumption on a year-to-year basis, however consumption has tended to remain stable at around 10,000 tonnes over the last 5 years.

In 2009 the QPS consumption exceeded non-QPS for the first time, being 46% higher. In 2017, reported QPS consumption was 70 times larger than controlled consumption and because controlled consumption is now nearly zero, this figure was very close to 100% in 2021. QPS uses of methyl bromide thus contribute nearly all of the global emissions of methyl bromide (Chapter 4). Control of these emissions is the biggest immediate gain that can be made under the Montreal Protocol to the reduction of ODS substances in the stratosphere.

Improvements in recapture technologies and recognition by the parties of the first destruction technology for methyl bromide (TEAP, 2018) mean that technologies are now available to reduce the use of MB emissions. As the implementation of these technologies imposes a cost on the user, their uptake will most likely only occur if parties impose regulations mandating their use.

Some countries have increased the strength of their quarantine regulations and procedures in response to pest movement and significant impacts. Many have also shifted from carrying out treatment on arrival to requiring a preshipment treatment.

5.2. QPS uses of methyl bromide

Quarantine and pre-shipment (QPS) treatments with methyl bromide (MB) are generally applied to commodities in trade between countries and between quarantine regions inside a country. QPS with methyl bromide (MB) are intended:

- To kill pests on perishable and durable commodities listed as quarantine pests (quarantine);
- On durable and perishable commodities or in trade to render them "practically free" of noxious pests (non-quarantine) and other organisms (pre-shipment).
- On soils, and in structures and commodities to eliminate or control exotic organisms of quarantine significance.

Periodic QPS uses of MB are sometimes made within countries in trying to prevent spread of exotic pests found in a new region. Since 2003, one party (i.e. USA) has interpreted that treatment to avoid movement of soil pests within a country on propagation material may also qualify for QPS MB use.

Most QPS use is on durable commodities where there tends to be a greater number of alternatives available. Durable commodities are those with low moisture content that, in the absence of pest attack, can be safely stored for long periods and include foods such as grains, dried fruits and beverage crops and non-foods such as cotton, wood products and tobacco and other non-agricultural goods that may harbor quarantine pests such as tires, household goods, and industrial goods. Perishable commodities include fresh fruit and vegetables, cut flowers, ornamental plants, fresh root crops and bulbs and even though many of these commodities are affected by MB fumigation, countries often still mandate its use.

MB has been in routine use for decades and is a well-developed system with a good record of success. Most current MB uses on durable and perishable commodities worldwide are highly specialized; detailed descriptions of specific treatments can be found in previous MBTOC reports.
Some specific examples of current QPS uses are:

- Fumigation of cut flowers found to be infested on arrival in the importing country with quarantine pests (quarantine treatment)
- Fumigation of fruit before export to meet the official phytosanitary requirements of the importing country for mandatory fumigation of an officially listed quarantine pest (quarantine treatment)
- Fumigation of grain before export to meet the importing country's existing import regulations that require fumigation of all export grain consignments (pre-shipment treatment)
- Fumigation of log exports either prior to shipment (pre-shipment) or on arrival against official quarantine pests (quarantine treatment).

Alternative treatments are often compared with the inherent properties of MB, which include such desirable features as:

- Rapid speed of treatment. This is particularly useful for perishable products that must be marketed rapidly;
- Low cost for fumigation;
- Relatively non-corrosive and applied easily to shipping fumigation facilities, containers or to bagged, palletised or bulk commodities ‘under sheets’;
- A long history of recognition as a suitable treatment by quarantine authorities;
- Broad registration for use;
- Good ability to penetrate into the commodity where pests might be located; and
- Rapid release of gas from the commodity after exposure

However, MB also has several undesirable features for example:

- High toxicity to humans;
- Odourless, which makes it difficult to detect;
- A significant ozone depleting potential;
- Adverse effects on some commodities, particularly loss of viability, quality reduction, reduced shelf life and taint;
- Slow desorption from some commodities and at low temperatures, leading to hazardous concentrations of MB in storage and transport subsequent to fumigation (Hall et al., 2017);
- Excessive bromide residues retained in the product.

In certain situations, MB is the only treatment approved by national quarantine authorities for QPS applications for international trade. Quarantine treatments are supported by extensive scientific data documenting the responses of pests to MB to verify a high level of treatment efficacy for pests that are serious threats to the importing country. Intra-country quarantines are aimed at curtailing, containing or eradicating spread of quarantine pests that may be established in a limited area or region of that country. In some cases, production of propagation material of certified high plant health status is considered a quarantine activity.

Pre-shipment treatments are aimed at ensuring that products in international trade meet set standards that qualify them as “pest-free”

5.3. Quarantine and pre-shipment – definitions under the Montreal Protocol

5.3.1. Origin and original intent of the QPS exemption

At the 1992 Meeting of the Parties in Copenhagen that established methyl bromide as a controlled Ozone Depleting Substance, Article 2H of the Protocol specifically excluded QPS from control measures when it stated, inter alia:

> *‘The calculated levels of consumption and production ...shall not include the amounts used by the Party for quarantine and pre-shipment applications’*

This was the first time that QPS was mentioned in the Protocol documentation. The definition of ‘quarantine’ and ‘pre-shipment’ was deferred to a later meeting.

At the time that Article 2H was agreed in Copenhagen in 1992, the Parties understood that there were no alternatives to MB for a diverse range of treatments carried out with MB for QPS. The Parties recognized that although QPS consumption was about 10% of global MB consumption at the time, this volume was nevertheless very significant in allowing inter- and intra-country trade in commodities in the absence of site-specific alternatives.

Unless site specific alternatives to MB were available for QPS that were tested and approved in both A 5 and non-A 5 countries, there was a strong likelihood of disruption to international trade if the exemption for QPS were not available.

Invasions by new pest species into a country or region can have serious adverse effects economically and on agricultural production and natural resources. The combined economic costs of new pests may be significant, with implications for environmental policy and resource management; yet full economic impact assessments are rare at a national scale.

The containment and eradication of a newly discovered pest is generally difficult, often highly controversial, and frequently requires substantial resources costing millions of dollars and the commitment of all involved, however there are many examples of successful eradication campaigns (MBTOC, 2011). Methyl bromide treatment is considered an important tool for some eradication and containment attempts. For example, it was successfully used in the eradication of khapra beetle from Western USA in the 1950s, and more recently to contain and possibly eradicate the exotic nematodes *Globodera pallida* and *G. rostochiensis* in parts of USA (TEAP, 2009).

5.3.2. 'Quarantine' and 'Pre-shipment'

The scope of the QPS exemption set out in Article 2H paragraph 6 has been clarified in Decisions VII/5 and XI/12 of the Protocol relating to the terms 'Quarantine' and 'Pre-shipment'. TEAP (2002) has provided some discussion and examples of cases that might or might not fall within the QPS exemption. There is also discussion of the scope of the exemption from control under the Protocol for QPS uses of methyl bromide in TEAP (1999) and the UNEP/IPPC (2008) publication 'Methyl Bromide: Quarantine and Pre-shipment Uses'. Differences in interpretation of the scope and application of the QPS exemption by individual Parties have led to some differences in the uses that were reported as QPS in the data accessed by MBTOC.

Specifically, the Seventh Meeting of the Parties decided in Decision VII/5 that:

"Quarantine applications", with respect to methyl bromide, are treatments to prevent the introduction, establishment and/or spread of quarantine pests (including diseases), or to ensure their official control, where:

> *Official control is that performed by, or authorised by, a national plant, animal or environmental protection or health authority;*

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.

"Pre-shipment applications" are those treatments applied directly preceding and in relation to export, to meet the phytosanitary or sanitary requirements of the importing country or existing phytosanitary or sanitary requirements of the exporting country.

The definition of 'Pre-shipment' is unique to the Montreal Protocol. It is given and elaborated in Decisions VII/5 and XI/12. The Eleventh Meeting of the Parties decided in Decision XI/12 that 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". As per decision VII/5, official requirements are those, which are "performed by, or authorized by a national plant, animal, environmental, health or stored product authority".

The definition of a quarantine pest under the Montreal Protocol differs from that under the IPPC (International Plant Protection Convention) by one word, 'economic': the Montreal Protocol refers to "pests of potential importance" while the Convention definition refers to "pests of potential economic importance". However, under the IPPC, it has been clarified in a supplement to ISPM No. 5 that ‘economic’ includes the effect of changes (e.g., in biodiversity, ecosystems, managed resources or natural resources) on human welfare.

The IPPC deals with pests of plants, and not of livestock, which would have potential economic impact, again including environmental considerations. The scope of the IPPC is analyzed in further detail in MBTOC and TEAP reports (MBTOC 2018, TEAP 2021, 2022). Its definition of a quarantine pest relates to official control, specifically pests of propagation material and seeds for planting, and do not include pests that affect quality in storage.

The Montreal Protocol’s definition covers environmental and other pests that might endanger a region without direct quantifiable economic loss. An interpretation of Decision VII/7 is that the use of methyl bromide as a quarantine treatment may only be for pests that are officially recognized as quarantine pests and must be officially authorized by a competent authority.

QPS treatments under the Montreal Protocol relate not only to official phytosanitary treatments, but may also apply to ‘sanitary’ treatments, e.g., against human or animal pathogens and vectors (e.g., mosquitoes), covered by International Agreements (IAs, multilateral agreements) such as the World Animal Health Organization (OIE) and World Health Organization (WHO).

Pre-shipment treatments target non-quarantine pests that may be present in both the exporting and importing country. These pests are usually ones that affect storage or end-use quality of the exported commodities and are outside the direct scope of the IPPC. However, the model Phytosanitary certificate from Guidelines for Phytosanitary Certificates provided in ISPM 12 contains the following optional clause: “They are deemed to be practically free from other pests.” This relates to Pre-shipment uses where a certification is needed to meet commodity shipping requirements. As a result of the broad coverage of the Montreal Protocol QPS concept, the actual QPS uses are covered by several different International Agreements and domestic regulatory bodies.

5.4. Decisions relating to QPS use of methyl bromide

Since 1992, there have been various Decisions taken by the Parties to the Montreal Protocol related to this QPS exemption. These have concerned definitions and clarification of definitions and have also requested TEAP to conduct closer evaluations of MB uses for QPS purposes and their possible alternatives or opportunities for reducing emissions. TEAP has responded to these Decisions through its MBTOC as well as appointing special task forces when necessary. A new Decisions specifically dealing with QPS uses of MB was recently taken by the Parties to the Montreal Protocol at the 34th MOP.

Table 5-1 lists decisions relating to QPS uses of MB and summarizes the main issues comprised by each. Reports prepared in response to such Decisions – when requested by the Parties – can be found at the Ozone Secretariat website.

TABLE 5-1: SUMMARY OF DECISIONS RELATING TO QPS USES OF METHYL BROMIDE

Decision No.	Decision title	Summary
VI/11(c) 1994	Clarification of «quarantine» and «pre-shipment» applications for control of methyl bromide	Gives definitions of quarantine and pre-shipment. Urges non-A5 Parties to refrain from MB use and use non-ozone-depleting technologies whenever possible. Where MB is used, Parties are urged to minimise emissions and use containment and recovery and recycling methodologies to the extent possible
VII/5 1995	Definition of «quarantine» and «pre-shipment» applications	Provides definitions for QPS. In applying them, all countries are urged to refrain from the use of MB and to use non-ozone depleting technologies when possible. Where MB is used, Parties are urged to minimise emissions and use MB through containment and recovery and recycling methodologies to the extent possible
X/11 1998	Quarantine and pre-shipment exemption	Requests TEAP to assess volumes and uses of MB under the QPS exemption, and to report on existing and potentially available alternatives, on the operation of the QS exemptions as per Decision VII/5 and on options that Parties might consider to reduce use and emissions of MB for QPS. Further to review and report on IPPC definitions for QPS.
XI/12 1999	Definition of pre-shipment applications	Defines a maximum time period of 21 days prior to export for application of treatments to qualify as 'Pre-shipment'
XI/13 1999	Quarantine and pre-shipment	Requests that the 2003 TEAP Report evaluate the technical and economic feasibility of alternatives that can replace MB for QPS uses; and to estimate the volume of MB that would be replaced by the implementation of such alternatives, reported by commodity and/or application. Requests Parties to review their national regulations with a view to removing the requirement for the use of MB for QPS where alternatives exist. Urges Parties to implement procedures to monitor the uses of MB by commodity and quantity for QPS uses. Encourages the use of recycling and recovery technologies for those uses with no feasible alternatives
XVI/10 2004	Reporting of information relating to quarantine and pre-shipment uses of methyl bromide	Requests TEAP to establish a QPS Task Force to prepare the report under Dec XI/13; requests Parties to submit information on QPS uses of MB if not already done so. Requires TF to report on the data submitted by Parties in response to the April 2004 methyl bromide QPS for the 25th OEWG. Data to be presented in a written report in a format aggregated by commodity and application so as to provide a global use pattern overview, and to include available information on potential alternatives for those uses identified by the Parties' submitted data
XVII/9 2005	Critical-use exemptions for methyl bromide for 2006 and 2007	To request the QPSTF to evaluate whether soil fumigation with MB to control quarantine pests on living plant material can in practice control pests to applicable quarantine standards, and to evaluate the long-term effectiveness of pest control several months after fumigation for this purpose, and to provide a report in time for the 26th meeting of the OEWG.

Decision No.	**Decision title**	**Summary**
XX/6 2008	Actions by Parties to reduce methyl bromide use for quarantine and pre-shipment purposes and related emissions	Requests the QPSTF, in consultation with the IPPC secretariat, to review all relevant, currently available information on the use of MB for QPS applications and related emissions; to assess trends in the major uses; available alternatives; other mitigation options and barriers to the adoption of alternatives; and to determine what additional information or action may be required to meet those objectives.
XXI/10 2009	Quarantine and pre-shipment uses of methyl bromide	Requests the TEAP and its MBTOC in consultation with other relevant experts and the IPPC to submit a review on the technical and economic feasibility of alternatives for a. Sawn timber and WPM (ISPM 15); b. Grains and similar foodstuffs; c. Pre-plant soil use; and d. Logs, including their current availability and market penetration rate and their relation with regulatory requirements and other drivers for the implementation of alternatives. Also requests an update on estimated replaceable quantities of MB used for QPS purposes distinguishing between A5 and non-A5 parties and a description of a draft methodology including assumptions, limitations, objective parameters and variations within and between countries that TEAP would use for assessing the technical and economic feasibility of alternatives, of the impact of their implementation and of the impacts of restricting the quantities of MB production and consumption for QPS
XXIII/5 2011	Quarantine and pre-shipment uses of methyl bromide	Invited Parties in a position to do so to report on the amount of MB used to comply with phytosanitary requirements of destination countries, and on phytosanitary requirements for imported commodities that must be met with MB. And requested TEAP/MBTOC to summarize article 7 data on QPS and provide regional analysis; provide guidance on procedures and methods for data collection on MB use for QPS; and prepare a concise report based on responses received.
XXIV/15 2012	Reporting on information on quarantine and pre-shipment use of methyl bromide	Requested Parties to comply with the reporting requirements of Article 7 and to provide data on the amount of methyl bromide used for quarantine and pre-shipment applications annually and invited Parties in a position to do so, on a voluntary basis, to supplement such data by reporting to the Secretariat information on methyl bromide uses recorded and collated pursuant to the recommendation of the Commission on Phytosanitary Measures. A possible request to TEAP to undertake a trend analysis of MB consumption in the QPS sector to be considered at the OEWG33 and MOP25
XXXIV/10 2022	Stocks and quarantine and pre-shipment uses of methyl bromide	Invites parties to submit a list of pest and commodity combination in which MB is used or needed, plus data on pre phase-out MB stocks. Requests MBTOC to provide updated information on current QPS uses for which alternatives are available, in consultation with IPPC

Source: Montreal Protocol Handbook and Ozone Secretariat website, 2018

5.5. Policies on QPS uses of methyl bromide

5.5.1. Legislation that requires methyl bromide use for QPS

Use of MB for QPS is mostly associated with international trade where regulations are usually imposed by the importing country on the exporting country. MB is used in response to either pests found during inspection and/or needed for a phytosanitary certificate, which requires the commodity to be free from quarantine pests and MB may be used or certified that MB has been applied at the rate required by the importing country. The driving force for what treatments are required, allowed or not allowed, are those of the importing country. In the case of bilateral trade and quarantine use, the importing country may allow the treatment to be conducted in the importing country, but often the treatment must be conducted in the exporting country. In many cases, QPS use of MB is covered by a number of national and local regulations, which often need to be considered in conjunction with one another.

There are also instances where internal regulations are imposed by national or state jurisdictions to use MB for movement of commodities across state or county borders. These relate to movement of quarantine pests that are known to be absent within the state or county.

MBTOC has encountered very few regulations that required or specified MB use only, however those that do tend to use substantial amounts of MB such as in the log trade. Examples are MB log treatments for countries exporting to China and India, which are to be applied by the exporting country to control quarantine pests and requiring a phytosanitary certificate with the treatment details. For China, MB fumigation is required for logs that have not been debarked, with either phosphine or MB. (MPI 2021a). For India (MPI 2021 b), the alternative option to MB is heat treatment at 56°C and above (core temperature of wood) for 30 minutes which is not practical or cost effective for whole logs.

In addition, there are many regulations that require plants to be free of insect and other pests, with MB as the only practical fumigant available especially at portside in the importing country i.e., when inspection at the importing port finds quarantine pests fumigation with MB may be the only available way to destroy the infestation, short of destroying the shipment. In cases where MB does not harm the commodity involved and treatment is relatively cheap, there may be little incentive to search for alternatives especially since these generally need to be developed in the exporting country, often lacking resources to do this. On a case by case basis, the cost of developing, registering, implementing and gaining acceptance of the trading partners of an alternative to replace a small volume of MB is often prohibitive.

Research to develop and confirm effectiveness of alternatives for quarantine treatments in international trade is expensive and time consuming, and generally must be done in the exporting country because only they have access to the pest in question. A very high level of efficacy (often Probit 9 – LD 99.9968%) is normally required for quarantine pests where methyl bromide fumigation is used as the major or sole control step.

As an example, below is useful information from New Zealand on the quarantine and trade with India (MPI (2022b) and presents part of the table in the MPI publication (table 5-2). It clearly shows why NZ needs to have access to MB under QPS:

> “Disclaimer
> The information in this standard is provided on the following basis. The phytosanitary requirements found in this standard may be used as the basis of export certification. However, requirements may be changed by importing countries at any time at short notice or with no notice to New Zealand. This information is provided strictly on the basis that the Crown, the Ministry for Primary Industries, its statutory officers, employees, agents and all other persons responsible for or associated with the compilation, writing, editing, approval or publication of the information:
> disclaim any and all responsibility for any inaccuracy, error, omission, lateness, or any other kind of inadequacy, deficiency or flaw in, or in relation to, the information; and
> without limiting (1) above, fully exclude any and all liability of any kind on the part of all of them, to any person or entity that chooses to rely on this information.
> Compliance with this standard is not to be taken as a guarantee that any particular goods will be granted access to any overseas market.
> Last Updated: 13 June 2022
> Commodities

Note: For India's import requirements for species not included here please contact MPI Plant Exports.

Table 5-2 illustrates the tedious efforts that are needed to replace quarantine treatments that have been developed over the years to disinfest logs thoroughly with MB. Comprehensive control data on all the mentioned pest organisms had to be provided before the uses of MB was accepted as quarantine method. So, all these control data must now be newly prepared in laboratory and field experiments to identify any alternative for MB use for the single pest organisms, before MB can be phased out from the respective sector.

TABLE 5-2: DETAILS FROM NEW ZEALAND ON INDIA'S IMPORT QUARANTINE REQUIREMENTS FOR TRADE OF VARIOUS LOGS

(Douglas fir, Pine, Eucalypt, etc.) and the necessary control of various pest organisms (taken in part from MPI (2021b).
Logs (Douglas fir)

Import Permits or Declarations	Import permit NOT required. Declarations required: "Free from: (a) *Hylastes ater* (Black pine bark) (b) *Otiorhynchus ovatus* (Strawberry root weevil) (c) *Pseudocoremia suavis* (d) *Heterobasidion annosum* (e) *Leptographium procerum* (White pine root decline) (f) *Ophiostoma piceae* (Vascular mycosis of oak) (g) *Phaeocryptopus gaeumannii* (Swiss needle cast) (h) *Phytophthora cryptogea* (tomato foot rot) (i) *Phytophthora megasperma* (root rot)) (j) *Amylostereum areolatum* (Sirex wasp fungus)."
Certification Requirements	Phytosanitary certificate required.
Prohibited Importations	
Bark	Not prohibited
Insects	
Fungi	Free from soil, earth, clay, compost, sand, peat and sphagnum moss.
Soil	Free from soil, earth, clay, compost, sand, peat and sphagnum moss.
Other	No information
Pre-Shipment Inspections	Verification inspection required.
Approved Pre-Shipment Treatments	Fumigation or heat treatment as below.
Fumigation	Methyl-bromide at: 48 g/m^3 at 21°C or above for 24 hours. 56 g/m^3 at 16-20° C for 24 hours. 64 g/m^3 at 11-15°C for 24 hours. 72 g/m^3 at 10-11°C for 24 hours
Antisapstain treatments	
Insecticide treatments	
Heat treatments	Heat treatment at 56°C and above (core temperature) for 30 minutes.

Preservative treatments	
Concessional Release	-
General	Fumigation on arrival prohibited

Logs (Pine)

Import Permits or Declarations	Import permit NOT required. Declarations required: "Free from: Branch and trunk cankers (*Atropellis piniphila, A. pinicola*) Pine wood nematode (*Bursaphelenchus xylophilus*) Cerambicid vector (*Monochamus* spp.) Pine beetle (*Tomicus piniperda*) and pine weevils (*Pissodes* spp.) Sirex wasp (*Sirex* spp)"
Certification Requirements	Phytosanitary certificate required.
Prohibited Importations	
Bark	Not prohibited
Insects	Free from quarantine pests including: *Bursaphelenchus xylophilus* (Pinewood Nematode) *Monochamus* spp. (Sawyer Beetle) *Tomicus piniperda* (Pine beetle) and *Pissodes* spp. (pine weevils) *Sirex* spp. (Sirex Wasp)
Fungi	Free from quarantine pests including: *Atropellis piniphila* and *Atropellis pinicola* (Branch and trunk cankers)
Soil	Free from soil, earth, clay, compost, sand, peat and sphagnum moss.
Other	No information
Pre-Shipment Inspections	Verification inspection required.
Approved Pre-Shipment Treatments	Fumigation or heat treatment as below.
Fumigation	Methyl-bromide at: 48 g/m3 at 21°C or above for 24 hours 56 g/m3 at 16-20°C for 24 hours 64 g/m3 at 11-15°C for 24 hours 72 g/m3 at 10-11°C for 24 hours
Antisapstain treatments	
Insecticide treatments	
Heat treatments	Heat treatment at 56°C and above (core temperature of wood) for 30 minutes.
Preservative treatments	
Concessional Release	-
General	Fumigation on arrival prohibited

Logs (C)

Import Permits or Declarations	Import permit NOT required. Declarations required: "Free from: *Ctenarytaina spatulata* *Gonipterus scutellatus* (eucalyptus snout beetle) *Paropsis charybdis* (eucalyptus tortoise beetle)

	Phoracantha semipunctata (eucalyptus longhorned borer) *Phytophthora cryptogea* (tomato foot rot) *Thaumastocoris peregrinus* (bronze bug) *Uraba lugens* (eucalypt leaf skeletonizer)"
Certification Requirements	Phytosanitary certificate required.
Prohibited Importations	
Bark	Not prohibited
Insects	Free from quarantine pests including: *Ctenarytaina spatulata* (Eucalyptus Shoot Psyllid) *Gonipterus scutellatus* (Gum Tree Weevil) *Paropsis charybdis* (Eucalyptus Tortoise Beetle) *Phoracantha semipunctata* (Eucalyptus Longhorned Borer) *Thaumastocoris peregrinus* (bronze bug) *Uraba lugens* (eucalypt leaf skeletonizer)
Fungi	Free from quarantine pests including *Phytophthora cryptogea* (tomato foot rot).
Soil	Free from soil, earth, clay, compost, sand, peat and sphagnum moss.
Other	No information
Pre-Shipment Inspections	Verification inspection required.
Approved Pre-Shipment Treatments	
Fumigation	Methyl-bromide at: 48 g/m^3 at 21°C or above for 24 hours 56 g/m^3 at 16-20°C for 24 hours 64 g/m^3 at 11-15°C for 24 hours 72 g/m^3 at 10-11°C for 24 hours

Forest Products Export Standards - Phytosanitary Requirements of India | NZ Government (mpi.govt.nz)

5.5.2. Policies and recommendations on methyl bromide and its alternatives under the International Plant Protection Convention

Some international standards produced by the IPPC (ISPMs) relate directly or indirectly to phytosanitary (quarantine) processes that either use methyl bromide at present or avoid the need for QPS methyl bromide treatments. The main standards relating to methyl bromide are:

ISPM No. 02 (2007) Framework for pest risk analysis
ISPM No. 10 (1999) Requirements for the establishment of pest free places of production and pest free production sites
ISPM No. 11 (2004) Pest risk analysis for quarantine pests including analysis of environmental risks and living modified organisms
ISPM No. 12 (2001) Guidelines for phytosanitary certificates
ISPM No. 14 (2002) The use of integrated measures in a systems approach for pest risk management
ISPM No. 15 (2006) Treatment of Wood Packaging Materials
ISPM No. 16 (2002) Regulated non-quarantine pests: concept and application
ISPM No. 18 (2003) Guidelines for the use of irradiation as a phytosanitary measure
ISPM No. 21 (2004) Pest risk analysis for regulated non quarantine pests
ISPM No. 22 (2005) Requirements for the establishment of areas of low pest prevalence
ISPM No. 24 (2005) Guidelines for the determination and recognition of equivalence of phytosanitary measures
ISPM No. 26 (2006) Establishment of pest free areas for fruit flies (Tephritidae)
ISPM No. 28 (2009) Phytosanitary treatments for regulated pests

ISPM No. 29 (2007) Recognition of pest free areas and areas of low pest prevalence
ISPM No. 30 (2008) Establishment of areas of low pest prevalence for fruit flies (Tephritidae)

The main ISPM that specifically deals with a major volume use of methyl bromide is ISPM 15, as revised (IPPC 2009b). The standard deals with the disinfestation of wood packaging material in international trade as a quarantine measure against various pests of wood and forests and contains specifications for both heat treatment and methyl bromide fumigation, whilst recognising that methyl bromide is an ozone-depleting substance (IPPC 2006, 2009). The ISPM 15 standard was revised in 2009 and encourages national quarantine authorities to promote the use of an approved MB alternative: 'NPPOs are encouraged to promote the use of alternative treatments approved in this standard' (CPM-4 report, April 2009, p.11 of Appendix 4).

ISPM 15 was updated at CPM-8 in April 2013, incorporating another heat treatment, the dielectric heating (e.g., microwave, radio frequency), for wood packaging material composed of wood not exceeding 20 cm that must be heated to achieve a minimum temperature of 60 °C for one continuous minute throughout the entire profile of the wood (including its surface). The prescribed temperature must be reached within 30 minutes from the start of the treatment. The Technical Panel on Phytosanitary Treatments (TPPT) of the IPPC accepted the treatment schedule without a thickness limit and recommended the IPPC Standards Committee to send it for member consultation.

Dielectric heating Radio frequency (RF) uses much lower frequencies than microwaves (MW), so the RF wave has a longer penetration depth than the MW and can be used to treat wood with larger dimensions than the 20 cm accepted by ISPM 15. Another characteristic of dielectric heating (DH) is the potential for selectively heat materials, offering an advantage over conventional heating for insect control due to the selective heating of insects due to their higher water content in relation to the wood itself. Another advantage of dielectric heating systems is that they are reported to convert 50–70% of the energy to heat, in comparison to 10% efficiency in conventional ovens.

More recently (2018) sulfuryl fluoride (SF) was approved by IPPC for compliance with ISPM-15. This adds a new alternative option, however MBTOC considers it important to note the high Global Warming Potential (GWP) of this fumigant (Vassileios et al., 2008, Mühle et al., 2009).

Alternatives for treatments of logs - not yet approved by IPPC - include application of phosphine, ethane dinitrile (EDN, cyanogen), heat (including vacuum steam), and debarking. Ethane dinitrile is registered in New Zealand and is close to registration in several other countries (Hall, pers. comm 2022) and with a growing amount of efficacy data, EDN has potential to replace a significant portion of QPS use for non-food items, formerly carried out with MB (e.g., Park et al. (2021).

5.6. Production and consumption of MB for QPS uses

5.6.1. Introduction

Since 1999 a continuous reduction in controlled uses of methyl bromide ("non-QPS") has occurred, as alternatives have been adopted for virtually all previous uses in observance of the phase-out deadlines agreed under the Protocol. By the end of 2021, 99.9% of global controlled uses had been replaced with alternatives.

In contrast, QPS consumption has not decreased but remained relatively constant over the last decade, as shown in Figure 3.2. In 2009 the QPS use exceeded non-QPS for the first time, being 46% higher. This was partly due to the continued decrease in the non-QPS uses, as well as re-categorisation by some Parties of uses previously considered non QPS to QPS. Since 2003 an amount of methyl bromide included in the initial baseline estimates for controlled MB uses, (an estimated 1400 to 1850 t), has been re-categorised to QPS MB use for the pre-plant soil treatment of propagation material.

Presently, only 2.5% of total global MB uses are for controlled uses, with the remaining 97.5% corresponding to QPS (exempted uses).

5.7. Main Uses of Methyl Bromide for QPS purposes

5.7.1. Main individual categories of use by volume

At various stages since 1994, TEAP and MBTOC have carried out surveys and/or contacted national experts in order to compile information about major QPS uses, and to estimate methyl bromide volumes used in some cases (e.g., MBTOC 1995, 1998, 2003, 2007, 2011, 2014, 2018). In 2022, MBTOC conducted a new survey on QPS uses amongst Parties reporting QPS consumption of 20 ODP (33 metric tonnes) or larger, with help from the Ozone Secretariat; this provided a list of 25 A-5 Parties and 4 non-A5 Parties. Responses were received from about half of these Parties, providing very helpful information. MBTOC notes that several Parties indicated not having such information available, either because such information on specific uses is not kept by phytosanitary authorities, or because resources to conduct this kind of analysis were not available. It was also noted that various respondents were not able to classify uses as “quarantine” or “pre-shipment” as requested in the survey or seemed to classify these uses erroneously.

In keeping with past Decisions (i.e., XX/6), MBTOC followed the same categories of use for QPS as those used by the IPPC, with some additions and modifications. These were as used in Annex 6 of 3CPM – Recommendation for the replacement or reduction of the use of methyl bromide as a phytosanitary measure (IPPC 2008) and are given in Table 5-3. The additional categories marked with an asterisk in were added to cover areas not covered by the IPPC.

TABLE 5-3. MAIN CATEGORIES OF MB USE FOR QPS PURPOSES

Category	**Uses**
Commodities	Bulbs, corms, tubers and rhizomes (intended for planting)
	Cut flowers and branches (including foliage)
	Fresh fruit and vegetables
	Grain, cereals and oil seeds for consumption including rice (not intended for planting)
	Dried foodstuffs (including herbs, dried fruit, coffee, cocoa)
	Nursery stock (plants intended for planting other than seed), and associated soil and other growing media
	Seeds (intended for planting)
	Soil and other growing media as a commodity, including soil exports and soil associated with living material such as nursery stock*
	Wood packaging materials
	Wood (including sawn wood and wood chips)
	Whole logs (with or without bark)
	Hay, straw, thatch grass, dried animal fodder (other than grains and cereals listed above)
	Cotton and other fibre crops and products
	Tree nuts (e.g. almonds, walnuts, hazelnuts)
Structures and equipment	Buildings with quarantine pests (including elevators, dwellings, factories, storage facilities)
	Equipment (including used machinery and vehicles) and empty shipping containers and reused packaging

Category	**Uses**
Soil as agricultural land*	Pre-plant and disinfestation fumigation of agricultural land*
Miscellaneous small volume uses	Personal effects, furniture, air* and watercraft*, artifacts, hides, fur and skins

Source: IPPC (2008) list of categories; *Not on IPPC (2008) list

5.7.2. Quantity of methyl bromide used

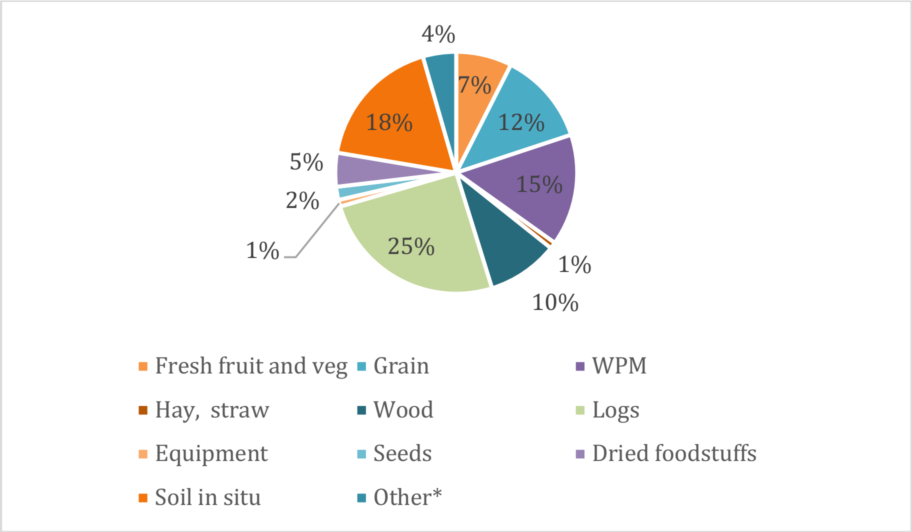
A general analysis on categories of use by volume for QPS MB use was conducted in a survey in 2022. On the basis of information received from key Parties information was categorized where possible into categories as stated above and supplemented by information contained in past QPS reports (TEAP 2009, 2012; MBTOC 2011, 2015, 2019).

Previous analyses indicated that the five largest consuming categories of methyl bromide for QPS:

- Sawn timber and wood packaging material (ISPM-15)
- Grains and similar foodstuffs
- Pre-plant soils use and
- Logs
- Fresh fruit and vegetables

The current survey shows that these categories continue to be the primary categories of use, although with some variations: for example fresh fruits and vegetables show a more prominent presence whilst use for wood packaging materials (ISPM-15) seems to have decreased. This could however be influenced by the make up of the specific countries responding the survey in each of the years . It was noted that several countries indicated not having the information on categories of use available, and/or lacking the resources to gather it. Clearly, more detailed information on actual categories of MB use for QPS purposes, and whether these are intended for quarantine or pre-shipment is needed in order to conduct a more relevant analysis of feasible alternatives in the future.

FIG. 5-10: ESTIMATED GLOBAL CATEGORIES OF MB USE (QPS PURPOSES) IN 2021



Source: MBTOC surveys 2018 and 2022

5.8. Key quarantine pests controlled with methyl bromide

Target pests for QPS treatments vary from country to country even for the same commodity, and the procedures for handling the issue of defining the target pests may also differ.

For pre-shipment treatments required by official authorities, the objective of treatments is to produce goods that are 'pest-free', or sometimes to some standard sampling level. While in practice the target species are typically insect pests (beetles, moths and psocids) that are widely distributed and associated with quality losses in storage, treatments are also expected to eliminate the other living insect species that may contaminate commodities during harvesting, storage and handling, even when they do not pose a direct threat to the quality of the commodity.

For quarantine treatments, the National Plant Protection Organisations (NPPOs) of particular countries publish master lists of regulated pests, being recognised quarantine pest species. These can be found through the IPPC portal. Only some of these pests are controlled by methyl bromide as the treatment of choice or exclusive approved treatment.

Some quarantine authorities have regulations for species not found in their country that require quarantine action if the species is known to be a pest that would cause damage or vector diseases in their country or if there is evidence to suggest a risk of such damage. Likewise, species that would substantially endanger human or animal health or comfort, especially by spreading exotic disease, would likewise be considered a quarantine species.

Species of quarantine concern to one country will not necessarily be of concern to another country: the pest might attack a crop not grown in the country, climatic conditions in the country might not be favourable to establishment of the species or the country might already have the species in their country. Nonetheless, there are certain groups of organisms that are responsible for most quarantine action in the world currently involving methyl bromide treatment.

Table 5-4 shows the main target pests of quarantine significance in the major classes of methyl bromide use, by volume, for plant Quarantine purposes.

TABLE 5-4: MAIN TARGET PESTS OF PLANT QUARANTINE SIGNIFICANCE IN THE MAJOR CLASSES OF MB USE FOR QPS PURPOSES

Treated commodity or situation	**Main target quarantine pests**
Whole logs, not debarked	Various species of bark beetles, wood borers, *Sirex* spp., pinewood nematodes, fungi (oak wilt, *Ceratocystis ulmi*)
Solid wood packaging	Various species of bark beetles, wood borers, *Sirex* spp., pinewood nematodes (*Bursaphelenchus xylophilus*)
Grain and similar foodstuffs	*Trogoderma* spp., (particularly *T. granarium*), *Prostephanus truncates*, *Sitophilus granarius*, cotton boll worm, various snails
Fresh fruit and vegetables	Numerous species of Tephritidae (fruit flies), thrips, aphids, scale insects and other sucking bugs, various Lepidoptera and Coleoptera, various mites
Soil for crop production, including propagation material	Exotic nematodes such as the Pale Potato Cyst Nematode (*Globodera pallida*), Golden nematode (*Globodera rostochiensis*), exotic weeds (including *Orobanche* spp.). Regulations in the USA also allow general 'certification' of nematodes to be considered QPS.

Key quarantine pests that are sometimes controlled in international trade with methyl bromide that lie outside the scope of the IPPC include various mosquito species (human and animal disease vectors, nuisance species), tramp ant species including red imported fire ant (*Solenopsis invicta*) (animal and ecological health, invasive species), rodents (disease vectors, stored product pest), snakes (invasive species), and cockroaches (human health disease vectors).

5.9 Existing and potential alternatives for the major QPS use categories

Previous MBTOC and TEAP reports have provided details of existing and feasible alternatives for various QPS uses (e.g., MBTOC 1995, 1998, 2002, 2007, TEAP 1999, 2007, 2009, 2011, 2015, 2019). Previous MBTOC Assessment Reports (MBTOC 2002, 2007, 2011, 2015, 2018) provide detailed information and discussion of alternatives to QPS methyl bromide use on commodities in specific circumstances. Detailed reports on QPS and alternatives are further given in TEAP (2003), produced in response to Decision XI/13(4) and in TEAP (2009 ab, 2010) in response to Decisions XX/6 and XXI/10. When looking for alternative fumigants, there are various reports dating back many years such as Monro (1969), Bond (1984) and even Peters (1942). These old references contain interesting surveys on many chemical substances that may be suitable for replacement of MB in quarantine use today. Also, the fumigation guide written by Graver (2004), contains useful information on the implementation of other fumigants into the practice of quarantine treatments.

Existing alternatives to MB for QPS treatment of perishable and durable commodities are based on pre-harvest practices and inspection procedures, and various non-chemical (physical, ie cold, heat, modified atmospheres) and chemical treatments (e.g., Stejskal et al. (2021)). Quarantine treatments can be applied ‘post-entry’, for example when inspection finds a quarantine organism in the shipment at arrival or when treatments have been insufficient to adequately manage the risk of importing quarantine pests. Many countries prohibit imports of particular cargoes where the risk of carrying quarantine pests is unacceptable and there is no system or treatment available to manage this risk to an adequate level. This avoids the need for post-entry quarantine measures, including methyl bromide fumigation.

Treatment options are often more restricted for post-entry quarantine treatments than for pre-shipment. In many post-entry situations, fumigation with MB is the only technically and economically available and approved process to meet quarantine standards to allow importation, due to limited infrastructure to apply alternative. Cargoes are often containerized and removal (unpacking and treating) from the container is uneconomic. MB fumigation may be ordered before the commodity can be released for distribution and rejection or destruction remains the default option if the treatment is not carried out.

NPPOs may publish listings of approved treatments for imports, with specifications varying according to phytosanitary requirements of receiving countries and pest risk. Stejskal et al. (2020) investigated in this context for the first time the magnitude of populations of the infestation of legumes by stored-product bruchids imported in freight containers into Europe. These findings were important steps to define the importance and impact of the quarantine measures.

MB may be specified as a quarantine treatment, but often there are also approved alternatives. A listing of alternatives for various Quarantine uses was given in the IPPC recommendation (IPPC 2008) to its contacting Parties on preferential use of alternatives in place of MB, together with considerations affect the choice of a phytosanitary measure to replace methyl bromide use. The listing is reproduced in Table 5-5.

TABLE 5-5: EXAMPLES OF POTENTIAL PHYTOSANITARY TREATMENTS THAT CAN REPLACE OR REDUCE METHYL BROMIDE USE FOR QPS PURPOSES

List of articles fumigated	**Examples of phytosanitary treatments to consider to replace or reduce methyl bromide[8]**
Bulbs, corms, tubers and rhizomes (intended for planting)	Hot water, pre-plant quarantine soil sterilization (steam or chemical), pesticide dip, or a combination of these treatments
Cut flowers and branches (including foliage)	Controlled atmosphere (CO2, N2) + combination treatment, hot water, irradiation, phosphine, phosphine/carbon dioxide mixture, pyrethroids + carbon dioxide, ethyl formate + carbon dioxide
Fresh fruit and vegetables	Cold treatment, high-temperature forced air, hot water, irradiation, quick freeze, vapour heat treatment, chemical dip, phosphine, combination of treatments, ethyl formate + carbon dioxide
Grain, cereals and oil seeds for consumption including rice (not intended for planting)	Heat treatment, irradiation, ethyl formate, carbonyl sulphide, phosphine, phosphine + carbon dioxide, sulfuryl fluoride, controlled atmospheres (CO2, N2)
Dried foodstuffs (including herbs, dried fruit, coffee, cocoa)	Heat treatment, carbon dioxide under high pressure, irradiation, ethyl formate, phosphine, phosphine + carbon dioxide, controlled atmosphere (CO2, N2), sulfuryl fluoride, propylene oxide
Nursery stock (plants intended for planting other than seed), and associated soil and other growing media	Hot water, soil sterilization (steam or chemical e.g., methyl isothiocyanate (MITC) fumigants), pesticides dip, phosphine (pure gas mixed with CO2), combination of any of these treatments
Seeds (intended for planting)	Hot water, pesticide dip or dusting, phosphine, combination treatments
Wood packaging materials	Heat treatment, now including dielectric heating (contained in Annex 1 of ISPM No. 15 and its revisions). Further alternative treatments may be added in the future. Ethanedinitrile
Wood (including round wood, sawn wood, Wood chips)	Heat treatment, kiln-drying, removal of bark, microwave, irradiation, MITC/sulfuryl fluoride mixture, methyl iodide, chemical impregnation or immersion, phosphine, sulfuryl fluoride, ethanedinitrile
Whole logs (with or without bark)	Heat treatment, irradiation, removal of bark, ethanedinitrile, phosphine, sulfuryl fluoride. MITC/sulfuryl fluoride mixture, methyl iodide, dipping in water for more than thirty days and pesticide spraying on the surface above the water
Hay, straw, thatch grass, dried animal fodder (other than grains and cereals above)	Heat treatment, irradiation, high pressure + phosphine, phosphine, sulfuryl fluoride
Cotton and other fibre crops and products	Heat treatment, compression, irradiation, phosphine, sulfuryl fluoride CO2

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[8] Examples are given that are generally applicable and likely to meet prevailing standards for treatment or disinfestation. Some alternatives may not be appropriate on particular commodities within the general category or in specific situations.

List of articles fumigated	**Examples of phytosanitary treatments to consider to replace or reduce methyl bromide[8]**
Tree nuts (almonds, walnuts, hazelnuts etc.)	Carbon dioxide under high pressure, controlled atmosphere (CO2, N2), heat treatment, irradiation, ethylene oxide, ethyl formate, phosphine, phosphine + carbon dioxide, propylene oxide, sulfuryl fluoride
Buildings with quarantine pests (including elevators, dwellings, factories, storage facilities)	Controlled atmosphere (CO2, N2), heat treatment, pesticide spray or fogging, phosphine, sulfuryl fluoride, hydrogen cyanide.
Equipment (including used agricultural machinery and vehicles), empty shipping containers and reused packaging	Controlled atmosphere (CO_2, N_2), heat treatment, steam, hot water, pesticide spray or fogging, phosphine, sulfuryl fluoride, ethyl formate (mixed with CO_2).
Personal effects, furniture, crafts, artefacts, hides, fur and skins	Controlled atmosphere (CO_2, N2), ethyl formate (mixed with CO_2), heat treatment, irradiation, ethylene oxide, pesticide spray or fogging, phosphine, sulfuryl fluoride
Export Pine logs from New Zealand	Either 30 g/m^3 MB at >15°C or 40 g/m^3 MB at <15°C for 16 h would ensure quarantine security against forest insects in New Zealand export logs (Najar-Rodriguez et al., 2020a). These reduced MB concentrations are approximately 70% and 65%, respectively, lower than 80 g/m3 at >15 _C or 120 g/m3 at _15 _C.
Citrus export from South Africa	A systems approach for mitigating phytosanitary risk of *Thaumatotibia leucotreta* (Meyrick) was developed for citrus export from South Africa. The systems approach consists of: (1) preharvest control and measurements and post picking sampling, inspection, and packinghouse procedures; (2) post packing sampling and inspection; (3) shipping conditions. (Hattingh et al., 2020).
Grape exports from Chile	A systems approach for table grapes exported from Chile to the USA is now awaiting final approval after successfully completing all necessary regulatory stages and a negotiating process taking over 2o years. The bilateral agreement will allow grape producers in areas of low incidence of *Lobesia botrana* and *Brevipalpus chilensis* who comply with established requirements, to export table grapes without fumigation with MB (Rodríguez, 2022)

5.9.1 Alternatives to MB for nurseries exempted as QPS

In the US, MB continues to be used as a pre-plant soil fumigant for the production of various types of nursery materials under the QPS exemption. This exemption applies to a range of nursery industries, including strawberry runners, ornamental plants, turf, fruit and nuts. It further includes the forest nursery industry in the Pacific Northwest in States such as Washington and Oregon (Weiland et al., 2013, 2016).

Research into MB alternatives and into reducing fumigation rates with the use of high barrier films has reported that reduced rates of metham sodium and 1,3-D applied under Totally Impermeable Film® (TIF) were comparable to MB (also at reduced dosage under TIF) in particular for controlling Fusarium and Pythium, two of the most troublesome diseases affecting forest nurseries. Some additional adjustments in rates are still necessary, but it is apparent that these alternative fumigants can provide equivalent results for this application (Weiland et al., 2016).

In all other countries such a QPS exemption is not allowed and industries have sought alternatives. For instance, in the EU (MB was banned for all uses including QPS in 2010) the strawberry runner industry, which includes Spain, one of the largest producers of runners in the world, mainly use crop rotation, dazomet and metham sodium for pest and disease control, with good results (López-Aranda 2016).

5.9.2. Review on alternatives for log treatments with MB

Armstrong et al. (2014) have reviewed over 30 fumigants for treating logs; the review did not include PH_3 as it is already being used for around 65% of New Zealand export logs needing treatment, saving an estimated 1,200 tonnes of MB per year. The review identified:

Ethane dinitrile has recently been registered as an MB alternative for export logs in New Zealand and can potentially reduce MB use substantially. Studies determining the efficacy of EDN on the life stages of burnt pine longhorn beetle, *Arhopalus ferus* (Mulsant) and the effects of dose, moisture content, end-grain sealing, and load factor on EDN sorption rates were very useful for the registration (Hall et al., 2015).

Sulfuryl fluoride, a common timber and structural fumigant for termites is a second possibility, however, environmental issues (very high GWP) and the difficulty with efficacy against insect eggs cannot be overlooked.

Research in New Zealand is addressing the potential for using reduced rates and/or fumigation times when MB is used to control forest insects and positive results from this research could translate into significant reductions in MB use and cost savings to the log export industry.

Debarking: A significant proportion of logs are already debarked for export and further studies are needed to determine if in-forest debarking at point of harvest can meet phytosanitary requirements. This would establish a technological and economic baseline from which to compare the costs of alternative treatments.

5.9.3. Physical methods as alternative for quarantine treatments with MB

Promising non-chemical alternatives include irradiation (Hallman 2016, Nadel et al., 2018), heat and cold treatments, bark removal and vacuum/controlled atmospheres (UNEP 2016). Generally, the application of heat, cold or other physical factors- apart from irradiation - for quarantine may bring along the destruction or decay of quality of the treated objects, particularly when a very high degree of control of pest organisms must be achieved.

5.9.3.1. Cold

Cold treatments for controlling fruit flies in fresh produce are becoming more popular in the international trade for fruit and vegetables and are being adopted by the IPPC CPM (Commission of Phytosanitary Measures). See those listed under the section on IPPC.

5.9.3.2. Heat

Heat, in the form of hot water, was first used as a disinfestation treatment to treat seed potatoes for late blight in 1882. Heat treatment has been used to control fungal, bacterial, and viral diseases, plant-parasitic nematodes, and insect pests, but was shelved for about 50 years with the advent of nerve poisons (DDT, diazinon) and chemical fumigants such as methyl bromide.

Heat treatments not only control pests and diseases but are a benefit to certain plants by increasing rooting, budding, and vase life. Plants, sensitive to heat injury, can also be conditioned to tolerate heat treatments.

Hot water treatment for 45 to 49°C for 10 to 15 min disinfests flowers, foliage, potted plants, propagative cuttings, and media of many pests of quarantine significance, including ants, aphids, mealybugs, scale insects, plant-parasitic nematodes, snails, and slugs. Hot water dips of tropical propagative cuttings can be used to disinfest cuttings of insects, nematodes, and pathogens with the side benefit of increase in rooting.

For example, the false codling moth, *Thaumatotbia leucotreta*, is a major quarantine pest that hampers capsicum trade in sub-Saharan Africa. Mwando et al. (2022) evaluated the efficacy of hot water treatment against immature stages of T. leucotreta in bell pepper and its effect on the quality of the peppers. They found that the third-instar was the least susceptible and 44.23 min (43.22 min - 45.24 min 95% confidential limit (CL)) was estimated to be the minimum time required to attain 99.9968% control level of all immure stages, and they further confirmed that none of the 25,384 third instars exposed to 50 +/- 0.2 °C for 32 min survived and no significant effects such as weight loss on the peppers were observed.

Hot air at 40°C conditions plants, foliage, and flowers to tolerate hot water, and at 44°C controls thrips and other insects. Use of steam to pasteurize (65°C for >30 min) or sterilize (85°C for >30 min) plant media will disinfest the media of fungal and bacterial pathogens and plant-parasitic nematodes.

A serious pest of grain in Asia and Africa and quarantine pest for many countries of the world is the khapra beetle, *Trogoderma granarium*. Wilches et al. (2019) found the most heat-tolerant life stages were diapausing-acclimated larvae and diapausing larvae. An exposure of 1 h at 60°C achieved 99% mortality of diapausing larvae. Based on these results, an exposure of 2 h at 60°C was recommended to control *T. granarium* with high temperatures. To meet requirements for control of quarantine pests, exposure of up to 12 h at 50-60°C is recommended to cause probit 9 mortality. The authors mention that additional experiments are needed to get a better estimate of probit 9.

It is difficult to heat treat logs and firewood because of the relatively large cross-sectional dimension. Compared with hot air, steam has a greater heat capacity, and the condensation, without reducing the moisture content of wood, results in more efficient heat transfer. Also, the pressure gradient created by vacuum accelerates heat transfer through the wood cross section. The vacuum–steam system consists of a vacuum source, a controlling device, a flexible container, and a steam generator. Chen (2016) treated ash log diameters from Virginia that ranged from 16.5 cm to 27.9 cm on the small end in lengths of 1.82 m. A vacuum of 300 mm Hg or 500 mm Hg inside the container and steam was injected into the container. The steaming continued until the target 56°C was reached at the centre of the lengths. The treatment time for all the logs varied from 5.5 to 14.5 hours, including a vacuum and a holding time of 30 minutes (ISPM 15). The 1.82-m logs were cut into 40.6-cm-long bolts and then split into firewood, rarely larger than 15.2 cm on the wider side. The treatment time for firewood varied from 80 to 137 minutes, including a vacuum and a holding time at 56°C for 30 minutes at the core. There is no effect on quality, and the process can be tailored to different treatment capacities and is easily portable. Chen (2016) also tested five high value hardwood veneer export log species in an effort to ascertain the feasibility of continued treatment development. Relative heating rates to log centre, damage and value loss assessment due to treatment, and overall energy used during treatment were recorded for logs treated individually in a flexible polymer chamber. At 200 mm Hg vacuum, time to reach 56 C for 30 min to core ranged from 17 to 29 h, depending on density and log diameter. End checking varied by species, but veneer sawn from logs was largely unaffected in terms of yield and value. Energy used during treatments ranged from 54 to 205 kWh for individual logs. Results suggest that vacuum and steam as a phytosanitary treatment for hardwood veneer logs has potential.

A process treatment which is a treatment using a process of heating in food process at a factory that is considered enough to kill insect pests. A process treatment is utilized in Japan since 2004 for imported corn or maize seeds destined to be processed to a corn-starch. Basically, imported corn or maize seeds must be fumigated with MB or aluminum phosphide when plant quarantine pest is detected in the import plant quarantine inspection. However, corn or maize seeds exclusive use for corn starch producing are not required the fumigations and the process those corn or maize seeds gone through is approved as an alternative treatment. In the process treatment, the seeds need to be securely treated with hot water immersion at either 40°C for 24 hours or 45°C for 5 hours, and impurities collected during the process must be also properly treated with incineration, fumigation or other approved methods (MAFF, 2004). This process treatment is expected to expand to food processing for extracting edible oil from imported grains such as wheat, maize and soybean, because the oil extracting process is also including a heating process.

Radiofrequency (RF) power has been investigated by Lagunas-Solar et al. (2006) as a physical-thermal method for disinfecting and disinfesting various foods and non-food materials, including agricultural soils. Control of fungi and nematodes was effectively achieved.

RF applications are currently limited to frozen foods, fruit juices, post-baking drying, and some pasteurization processes due to high costs and uncertainty regarding the RF properties of foods and other materials. At the University of California at Davis, the use of new bands of the RF spectrum (few kHz to < 10 MHz) has been studied and tested successfully allowing significant cost reductions and operating with high energy efficiency.

A project developing radio frequency (RF) technology has generated the data required leading to approval of this method by the International Plant Protection Convention (IPPC) in compliance with ISPM-15 for wood packaging; but cost effectiveness needs to be improved for adoption in practice. In 2016, it was found that by adding pressure to the RF chamber during treatment dramatically reduced the treatment time, improved heating uniformity, and reduced energy and labor costs significantly.

Subsequent work by Heffernan et al 2018 using direct electrical energy showed that Joule heating can be adapted to successfully heat both softwood and hardwood logs to temperatures in the region of 60 to 70oC or so. Such heating requires in the order of 40kWh of energy per cubic metre of timber and can be sufficient both to eliminate pest insects (and other organisms) and to soften timber for veneer peeling and slicing more efficiently that hot water. Designs for a small pilot plant have been drawn and a funding source is needed to build

5.9.3.3. Irradiation

E-beam (electron beam) irradiation systems have progressed to the point that they might make irradiation more available for phytosanitary uses in the near future. Essentially, x-rays are generated electronically, and therefore, the radiation source can be turned on and off at will, a fact that makes e-beam technology safer than cobalt-60 and require less oversight and regulation. This technology has been available since the late 1990's but is finally moving into the early implementation stages for phytosanitation in the United States. However, phytosanitary regulatory agencies sometimes require rates that are damaging to the goods, and more research is needed to improve technical data on the minimal rates actually required for adequate phytosanitation (Hallman 2016). Although radiation has been around a long time, its use was somewhat limited in the United States, partly due to low consumer acceptance of irradiated goods, and economic cost. Whether the new e-beam technology will have higher acceptance and economic feasibility is not yet clear.

More companies are now offering improved and new machines. The manufacturers endeavour to cover a broad spectrum of energy and power and improve the reliability and durability. In order to reduce the initial investment, they are also offering a modular approach by which the power of the machine can be increased by steps, for example by adding another power supply unit. Many are now portable.

The Australia New Zealand Food Standards Code (the Code) allowed irradiation of fruit fly for from July 2021. At the Melbourne Market in Australia a new X-ray treatment has been built for phytosanitary treatment measure against fruit flies, using cutting-edge new technology for fresh horticultural produce that enables growers to meet export market access requirements. It is also a viable alternative to chemical treatment or prolonged cold storage of product.

Irradiation is a postharvest treatment option for exported berries and berry-like fruits to prevent movement of the quarantine pest European grape vine moth *Lobesia botrana* (Denis & Schiffermüller) (Lepidoptera: Tortricidae). The effects of irradiation on egg, larval, and pupal development in *L. botrana* were examined by Nadel (2018). Eggs, neonates, third and fifth instars, and early- and late-stage pupae were irradiated at target doses of 50, 100, 150, or 200 Gy, respectively, or left untreated as controls in replicated factorial experiments, and survival to the adult stage was recorded. Tolerance to radiation generally increased with increasing age and developmental stage. A dose of 150 Gy prevented adult emergence in eggs and larvae. Pupae were more radio tolerant than larvae, and late-stage pupae were more tolerant than early-stage pupae. In large-scale validation tests, 150 Gy applied to fifth instars in diet prevented adult emergence, but some survival occurred in fifth instars irradiated in table grapes; however, 250 Gy prevented fifth instar survival in grapes. For most commodities, the fifth instar is the most radio tolerant life stage likely to occur with the commodity; a minimum radiation dose of 250 Gy will prevent adult emergence from this stage. For traded commodities such as table grapes that may contain *L. botrana* pupae, 325 Gy applied to mature female pupae sterilized emerging adults and may provide quarantine security. Radio tolerance in *L. botrana* is comparable to other tortricids, and the data reported here support a generic dose of 250 Gy for eggs and larvae of this group. Use of irradiation for postharvest treatment of fresh commodities to free them from insect pests of quarantine concern continues to increase.

Haandel et al. (2017), described in the tolerance of *Hylurgus ligniperda* and *Arhopalus ferus* (Mulsant) to ionising radiation and compared it with existing generic radiation as a phytosanitary treatment.

In South Korea, Cho et al. (2019) examined the effects of gamma-ray irradiation on the development and reproductive sterility of whiteflies *Bemisia tabaci* and *Trialeurodes vaporariorum* (Hemiptera: Aleyrodidae) on exported strawberry fruit. They found that treatment with 100 Gy suppressed the development and reproduction of eggs and adults in both species.

Zhao et al. (2021) reported that the combination of modified atmosphere (MA) and ionizing radiation led to synergistic effects successfully controlling oriental fruit flies in irradiated fruit held in a 1% oxygen atmosphere for 14 or 15 days. This resulted in the required efficacy for quarantine standards of 99.9968% mortality at 95% confidence level.

Irradiation is used in Thailand as an alternative to cold treatment for control of oriental fruit flies, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), and other pests of mango fruits. Srimartpirom et al. (2018) found that low-O_2/ high-CO_2 modified atmosphere packaging (MAP) did not reduce the efficacy of the approved 150 Gy quarantine irradiation treatment for B. dorsalis. Further, modified atmospheres (carbon dioxide, nitrogen and ozone) proved to be effective in disinfesting cut lotus flowers after 9 h fumigation (Bumroongsook and Kilaso, 2018) for controlling common blossom thrip (*Frankliniella schultzei*), a major problem hindering exports of cut lotus flowers.

Embaby *et al*. (2022) investigated the effect of low doses of gamma irradiation range of (5-50 Gy) Cesium137 cell- on the different developmental stages: eggs, 1st, 2nd, 3rd instars larvae and pupae of peach fruit fly, *Bactrocera zonata*, and phytosanitary irradiation effects of the biochemical quality of guava fruits. The irradiation of eggs with 25 Gy prevented adult emergence, while 45 Gy prevented pupation and 50 Gy prevented the hatchability of eggs. No adult emergence was reported in 1st, 2nd, 3rd instars at 30, 35 and 45 Gy, respectively. After performing the large-scale confirmatory tests which applied to 25,000 of most tolerant 3rd instar larvae, the irradiation dose of 50 Gy induced the inhibition of adult emergence of 3rd instar larvae and was suggested as a possible minimum dose for phytosanitary treatment of *B. zonata* fruit fly without causing significant negative effects on some biochemical characteristics of guava fruits.

Codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), is a serious pest of apple, pear and occasionally, stone fruit (*Prunus persica* (L.)). Its presence in sweet cherries is rare and presumed to occur in area where high populations in pome fruits occur near sweet cherries, *Prunus avium* (L.). Nevertheless, the potential of codling moth residing in a sweet cherry destined for an export market, especially to Asian Pacific countries, has led to the continued use of methyl bromide, to prevent the accidental spread of this pest. Neven and Wakie (2020) treated the first three instars of codling moth in export-quality sweet cherries and found that the third instar was the most radio-resistant, requiring a dose of approximately 250 Gy to prevent adult emergence. Although this dose is higher than those reported for control of fifth-instar codling moth in apples and artificial diet but should not delay any efforts in using this highly effective treatment to meet quarantine restrictions against this pest.

Sanzharova and Loy (2022) assessed the current state of the use of ionizing radiation for insect pests in grain and grain products during storage in the Russian Federation. They found that gamma irradiation of the tobacco beetle (500 Gy/h) in the adult stage at doses of 400, 500 and 300 Gy resulted in complete mortality on days 4, 5 and 6, respectively. On the 9th day after irradiation, the complete death of the tobacco beetle was noted when irradiated at a dose of 200 Gy and on the 20th day at the dose of 100 Gy. In the larval stage, total mortality occurred at a dose of 500 Gy on 15th day, at doses of 100 - 400 Gy on the 22nd-31st day. The viability of khapra beetle larvae under gamma irradiation decreased by 100% at doses of 50-100 Gy after 4 - 5 days, at doses of 350 and 450 Gy after 7days, at doses of 100 and 300 Gy after 8 days and at other doses only after 14 - 17 days. Chemical composition of the irradiated grain of wheat and barley did not reveal any negative effect on the quality of Rima variety of wheat and Vladimir variety of barley. This technology can be easily integrated into the technological processes of grain storage and transportation.

5.9.4. Other fumigants as alternatives for quarantine treatments with MB

5.9.4.1. Hydrogen cyanide (HCN, BluefumeTM)

HCN continues to show promise as an alternative to MB South Korea for treatment of stem and bulb nematodes infesting garlic cloves (Zouhar et al., 2016) and New Zealand for some fruit. Malaysia reported registration of HCN in 2019/2020 as an alternative to MB for postharvest treatments (Glassey, pers. comm., 2021). Hnatek et al. (2018) described the prospects of BLUEFUME™, the name of HCN from Draslovka company, for pest control purposes.

HCN shows a promising level of biocidal activity on package and structural wood infesting pests such as *Hylotrupes bajulus, Anopolophora glabripennis* and pine wood nematode, *Bursaphelenchus xylophilus* (Stejskal et al., 2014; Douda et al., 2015). This compound is registered in Japan for phytosanitary treatment aimed at controlling scales, mealy bugs, aphids, thrips or whiteflies intercepted on imported commodities e.g., seedlings or fresh fruit. The fumigation schedule is prescribed by the related Ministry of Agriculture, Forestry & Fisheries (MAFF) at a dosage rate of 1.8 g/m3 for 30 minutes (MAFF 1978, MAFF 1987). Hall *et al* (2018), quantified HCN as a potential decomposition product of ethane dinitrile during pine log fumigation.

Residue patterns of HCN were investigated in South Korea and found safe; average residue levels on orange, banana and pineapple 3 days after a double dose fumigation treatment (HCN 6 g/m3, 2h, 15-20°C) were lower than the accepted MRLs of 5 mg/kg (Park et al., 2011). Stem and bulb nematodes (*Ditylenchus dipsaci*) infesting garlic cloves are efficiently controlled with HCN (Zouhar, et al., 2016).

HCN is also in use in New Zealand for the disinfestation of surface pests on bananas and pineapples such as scale and mealybug (Table 5-6). The HCN fumigation schedule is prescribed in the Approved Biosecurity Treatments Standard treatment schedule at a dosage rate of 3g/m^3 for two hours (plus 20 minutes for gas release from the HCN impregnated cardboard discs) carried out in chambers that are also used for the ripening process with ethylene (ACVM 2020).

TABLE 5-6: USE OF HCN FOR PHYTOSANITARY TREATMENT IN NEW ZEALAND

Application schedule	Recommended dosage in g/m3	Exposure time in hours	Temperature in °C
Storage pests in mills warehouse and food factories	5 to 12	6 to 48	15 or above
Rodents in empty warehouses, ships holds	2 to 4	2 to 4	4 or above
Nursery stock in dormant stage	5 to 10	0.5 to 1	15 or above
Storage pests in empty ships holds	10	10 to 12	5 to 9 or above
Bananas	3	2	13.5 to 15

Source: HCN Label NZ, ACVM 2020

BLUEFUME^{TM} (active ingredient: hydrogen cyanide, HCN):

Apart from use for structural fumigation (i.e., industrial buildings, processing plants, flour mills, empty structures, and ships), the company DRASLOVKA also aims with BLUEFUME at the fumigation of commodities like fresh fruits such as bananas, and pineapples. Registration of BLUEFUME has been obtained in New Zealand and the European Union. The target pests are insects and mites - including eggs -, like cigarette beetles, flour mites, lesser grain borers, weevils, rust-red flour beetles, Indian meal moths, poultry red mites, American cockroaches, bed bugs, and rodents (house mice, brown rats). In so far, the target pests belong not only to stored product pests, but also to hygiene pests, often covers by biocidal laws. The lethal exposure periods are in the range of 24 hours or even less.

Key points for BLUEFUME^{TM}

- Structural fumigant – industrial buildings, flour mills, empty structures
- Fresh produce
- Australian registration – expected by the end of 2022
- Short treatment time
- Low lethal dose rate

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5.9.4.2. Ethane dinitrile (C_2N_2, $(CN)_2$, Dicyan, Cyanogen, EDN)

Dicyan was very likely synthesized for the first time in 1782 by Carl Wilhelm Scheele when he was synthesizing HCN. In the literature, it is described as ethane dinitrile as well as ethanedinitrile.

Hnatek et al. (2018, 2021) gave information on EDN® to control soil, wood, timber, structural and stored product pest arthropods. Trials with EDN achieved 100% mortality of the European house borer, *Hylotrupes bajulus* within 24 h, under an environment of 25°C and75% relative humidity (Emmery et al., 2015).

Trials with this fumigant were also shown to achieve 100% mortality of the European house borer, *Hylotrupes bajulus* within 24 h, under an environment of 25°C and 75% relative humidity (Emmery et al., 2015). Hall et al. (2015) tested the sorption characteristics of EDN for recently harvested pine logs and tested an EDN sorption model for sawn timber. Over a 10-h period, average concentrations were 17.3% +/- 0.7 of the initial dose for logs with sealed ends and 9.4% +/- 0.4 for unsealed ends. This is a high rate of sorption compared with other fumigants, such as MB. A proportional drop in headspace concentration over time was consistent for the two doses (20 g/m^3 and 50 g/m^3) evaluated, confirming that EDN sorption is influenced by the dose applied. Bark cover did not significantly influence EDN sorption. Mass rearing of two species of *Scolytidae* and one *Cerambycidae* (Barrington et al., 2015;

Clare and George, 2016) have made it possible to supply high numbers of all life stages, never achieved before on a regular basis for fumigation trials.

Najar-Rodriguez *et al.* (2015) compared the toxicity of EDN in the laboratory to that of reduced rates of MB, using different life stages of the burnt pine longhorn beetle, *Arhopalus ferus*. Naked insects were fumigated with MB at 10°C and 20°C for 4 h or with EDN at the same temperatures for 3 h. Najar-Rodriguez *et al.* (2020b) more recently carried out large--scale commercial validation of the efficacy of ethane dinitrile. The mortalities achieved and the ct-products calculated indicate that;

(1) a reduction in MB usage may be possible for the treatment of logs exported from New Zealand, and
(2) EDN has potential as a phytosanitary alternative to MB for the treatment of logs.

Pranamornkith et al. (2014a; b) tested the control of burnt pine longhorn beetle (*Arhopalus ferus*) adults using a range of EDN concentrations. The Lethal Dose for 99.99% kill LD99 for adults after a 3 h exposure at 15°C was 12.6 g/m³. Changes in the dose of EDN did not affect the sorption pattern.

Increased moisture content and end-grain sealing both reduced sorption, but these effects were relatively small and the differences in sorption patterns caused by moisture content or end-grain sealing decreased over time. The sorption characteristics of EDN (syn. cyanogen, EDN Fumigas®) were quantified by Hall *et al.* (2015) for recently harvested pine logs, and a proposed EDN sorption model developed for sawn timber was tested, showing a high sorption rate as compared to other fumigants such as MB. A proportional drop in headspace concentration over time was consistent for the two doses evaluated (20 g/m³ and 50 g/m³), confirming that EDN sorption is influenced by the dose applied. Bark cover did not significantly influence EDN sorption.

Pranamornkith et al. (2014a) studied EDN at doses of 20 g/m³ or 50 g/m³, timber moisture content (green or kiln dried sawn timber), end-grain sealing (sealed or unsealed timber end-grain) and load factor (11% or 44%) on sorption of EDN by sawn timber at 15°C. This was quantified using headspace samples taken from 28-litre fumigation chambers. Chamber loading significantly influenced sorption, with higher loading resulting in greater sorption.

Changes in the dose of EDN did not affect the sorption pattern. Increased moisture content and end-grain sealing both reduced sorption, but these effects were relatively small and the differences in sorption patterns caused by moisture content or end-grain sealing decreased over time. These same researchers tested the efficacy of ethane dinitrile for controlling burnt pine longhorn beetle adults (*Arhopalus ferus*) using a range of EDN concentrations. The LD99 for adults after a 3 h exposure at 15°C was 12.6 g/m³.

The results demonstrate that EDN is a potential phytosanitary alternative to methyl bromide for disinfesting burnt pine longhorn adults from sawn timber exported from New Zealand. In Japan, the pinewood nematode, *Bursaphelenchus xylophilus* is a quarantine pest often associated with beetles of the genus *Monochamu*s (pine sawyers), particularly *M. alternatus*, which can disperse the nematodes to long distances causing widespread losses in pine forests. Lee et al. (2017) carried out preliminary experiments to control *M. alternatus* and *B. xylophilus* with ethane dinitrile. Park et al. (2014) conducted two fumigation trials on logs naturally infested with *M. alternatus* and *B. xylophilus*. The logs were treated with EDN at low temperature (-7 to -25.7°C and -3.7to -23.1°C) for 3 days in winter and early spring. Results suggest that 97 g/m3 of EDN gives complete control of *M. alternatus* in pine wood and that dosages above 158 g/m3 are required for eradication of *B. xylophilus* at low temperature fumigation. Park et al. (2014) also compared EDN and metam sodium for control of *B. xylophilus* and *M. alternatus* in naturally infested logs at low temperatures.

Douda *et al.* (2020) have proposed an inexpensive screening method to validate the efficacy of ethane dinitrile fumigant on *B. xylophilus*. Bong-Su et al. (2015) verified the efficacy of EDN under different temperature conditions (5°C, 5°C to 15°C, >15°C) and monitored its TLV (Threshold limited value) post-fumigation for worker safety. Fumigation doses of 30 g/m³, 40 g/m³ and 50 g/m3, respectively, for 24 h for controlling ordinary pests of wood such as Japanese termite, *Reticulitermes speratus*, and bark beetle, *Cryphalus fulvus*, showed >99% efficacy at 5°C, 5 C to 15°C and >15°C, respectively. Doses of 100 g/m³, 120 g/m³ and 150 g/m3, respectively, for 24 h were also successful in achieving the required efficacy at 5°C, 5°C to 15°C, >15°C, respectively, meeting quarantine guidelines for wood related pests such as the Japanese pine sawyer, *Monochamus alternatus*, and the pine wood nematode, *Bursaphelenchus xylophilus*. Recommended ventilation times with atmospheric conditions at ports were > 1 h and > 2 h under fully uncovered and partially uncovered tent conditions, respectively.

M. alternatus Hopeis is an important vector of nematode pests of timber in Korea, particularly *B. xylophilus* (Steiner & Buhrer) Nickle. Previously, Lee (2015) had reported on the potential of EDN to replace MB and metham sodium to control *M. alternatus* larvae and *B. xylophilus* under low-temperature (<5°C) conditions. Fumigation trials with EDN were conducted over a 3-year period (February 2013–October 2015) at higher temperatures and under 24 different conditions that incorporated varying fumigation chamber types (plastic sheeting-enclosed chambers of differing construction or an ISO shipping container, interior size: 5.90 m length by 2.35 m width by 2.40 m height), log water content (24.1 - 43.5%), filling ratios (5, 20, and 40%), and temperatures (10.5 °C to 17.3°C). Highest concentration x time (ct) product values were obtained with the ISO shipping container followed (in order of decreasing ct values) by a 0.1-mm-thick, low-density polyethylene tarpaulin enclosure, a 0.1-mm-thick polyvinyl chloride (PVC) tarpaulin enclosure, and a 0.05-mm-thick PVC tarpaulin enclosure. The correlation between ct product value and mortality of *M. alternatus* larvae was calculated with all treatment combinations. From this, the L(ct) 50 and L(ct)99 values for EDN were determined to be 73.19 and 194.90 gh/m³, respectively. Ethane dinitrile showed promise as a practical alternative fumigant for use on fresh pine logs infested by *M. alternatus* larvae.

Based on preliminary laboratory studies on the efficacy of ethane dinitrile (C2N2) to *B. xylophilus* and *Monochamus alternatus*, Lee *et. al.,* (2107a, b) conducted three quarantine trials at three dosages and three temperatures. Potential for in halation exposure was assessed by monitoring atmospheric EDN in relation to the threshold limit value. Concentration time products (ct) of 398.6, 547.2 and 595.9gh/m³ were obtained for each trial. A 100% mortality of *B. xylophilus* and *M. alternatus* larvae at 23±4°C and 10 ± 4°C occurred with a load factor of pine logs of 46% and at 3±1°C with a load factor of 30%. During all fumigations, atmospheric levels of EDN 20m downwind were below the TLV. During aeration, levels 10 m and 5 m downwind were below the TLV after 0.4 and 1 h, respectively.

For the purpose of quarantine or phytosanitary treatment, specific doses of C2N2 at the trial temperatures could control *B. xylophilus* and *M. alternatus* larvae without significant inhalation risk to workers.

Registration of EDN in New Zealand as an alternative to MB can replace about 500 tonnes of methyl bromide (EPA NZ, 2022). Research on EDN as an alternative to MB for QPS uses, particularly for the treatment of timber and logs continues with promising results for example in New Zealand, the Czech Republic and Korea (Najar-Rodríguez et al., 2020; Stejskal et al., 2017). In addition, stored product pest insects like *Rhyzopertha dominica* and *Lasioderma serricorne* have been studied with EDN for desorption and efficacy (Ramadan et al. (2020).

Phosphine, SF and ED were tested against the pinewood nematode, in a range of artificially infested wood samples with high moisture content and, in some cases, the bark layer intact on the surface exposed to the fumigant. EDN was effective on pine chips, blocks and logs at all the doses tested: 40-100 mg/l for 24 h at 20°C. Ethane dinitrile appears to be a promising alternative to MB for the fumigation of pine logs in quarantine. The New Zealand Environmental Protection Agency (EPA) has approved EDN for use on export logs and timber but not imported logs and timber. This has the potential of reducing about 600 tonnes of MB per year, however some requirements still need to be met particularly in relation to safe application methods and acceptance by trade partners.

Malaysia and South Korea have registered EDN in 2019/2020 as an alternative to MB for postharvest treatments, logs and timber (Glassey, pers. comm., 2021, see table 5-3) (see table 5-7; Draslovka, MBAO 2020).

Pest research with EDN	Reference
A. glabripennis	Ren 2006
Anoplophora glabripennis	Ren 2006
Bursaphelenchus xylophilus	Seabright 2020
Bursaphelenchus xylophilus	Seabright 2020
Bursaphelenchus xylophilus	Uzunovic 2022
Bursaphelenchus xylophilus	Chung 2007
Bursaphelenchus xylophilus	Malkova 2016
Bursaphelenchus xylophilus	Lee 2017
Bursaphelenchus xylophilus	Stevens 2022
Bursaphelenchus xylophilus	Stevens 2022
Bursaphelenchus xylophilus	Park 2014
Cryphalus fulvus	Cho et al 2011
Dryocetes autographus	Stejski et al 2017 article
Dryocoetes hectographus	Stejski et al 2017 article
Hylurgops palliatus	Stejski et al 2017 article
Hylurgus ligniperda	Najar-Rodriguez 2020
Hyphanria cunea	Park et al 2009
Ips typographus	Stejski et al 2017 article
Lasioderma serricorne	Hooper et al 2003
M.alternatus	Park et al 2012
Monochamus.alternatus	Lee 2017
Pityogenes chalcographus	Stejski et al 2017 article
Reticulitermes speratus	Park et al 2009
Rhyzopertha dominica	Hooper et al 2003
Sitophilus oryzae	Hooper et al 2003
Tomicus piniperda	Park et al 2009
Tribolium castaneum	Hooper et al 2003
Trogoderma variabile	Hooper et al 2003

Major uses of EDN now comprise:

- Post-harvest phytosanitary treatment of import and export timber & logs for control of insects, nematodes, and pathogens
- Pre-plant soil treatment for control of nematodes, pathogens, and weeds in turf grass, sports turf, and golf courses
- Pre-plant soil treatment for control of nematodes, pathogens, and weeds in some horticultural crops such as strawberries, melons, and cut flower production

TABLE 5-7: ACTIVE REGISTRATIONS OF EDN

Country / Region	Registered Use
Australia	Timber & Logs and Preplant Soil Treatment
Malaysia	Timber & Logs and Preplant Soil Treatment
Korea	Timber & Logs
Russia	Timber & Logs
New Zealand	Timber & Logs

TABLE 5-8: PENDING REGISTRATIONS OF EDN

Country / Region	Requested Registered Use
USA	Timber & Logs
Uruguay	Timber & Logs
European Union	Timber & Logs
India	Timber & Logs
South Africa	Timber & Preplant Soil Treatment
Canada	Timber & Logs

5.9.4.3. Ethyl formate ($C_3H_6O_2$, Vapormate^{TM}, eFume^{TM})

EF is the oldest fumigant used since 1929 to disinfest dry fruits with present threshold limit value for workers (TLV) of 100 ppm for 8 hours and no maximum residue value for cereal grains and fresh fruit commodities is applicable when used as recommended (see Table 5-9). Ethyl formate (EF) is a Generally Recognized as Safe (GRAS) plant volatile compound. Its vapour is highly flammable with a lower flammability limit of 2.8% in air. While this is above typical fumigation concentrations, it needs dilution in practice to below the flammability limit from its liquid or concentrated form. Alternatively, the ethyl formate may be volatilized in a stream of nitrogen gas, as per Yang et al. (2016), who described this technique as used for disinfestation of oranges imported into South Korea. Ample research has been conducted in various countries with EF alone or combined with phosphine, CO2 or N2 (Yang et al., 2016; Jamieson et al., 2016; Grout and Stoltz, 2016; Park et al., 2020), or with ethane dinitrile (EDN) (Pranamornkith et al., 2014a, b; Park et al., 2014; Bong-Su et al., 2015).

EF has been used in trials to reduce incidence of external pests on apples to acceptable rates for export markets. For example, mealybugs, scale insects, thrips and apple leaf curling midge (ALCM) on packed New Zealand apples are a concern for export markets. A treatment of 0.3% EF +CO2 for 1 h controlled 99% of onion thrips and latania scale, and 0.81% EF + CO2 for 1 h controlled obscure mealybug. However, Jamieson *et al.* (2015) found treatment concentrations and times required to control ALCM (4.94% EF for 4 h) were beyond the apple quality tolerance level.

Yang *et al.* (2016) conducted a study to compare the effects of EF and phosphine (PH3) as individual treatments, and of EF mixed with phosphine (PH_3) as alternatives to MB for controlling citrus mealybug (*Planococcus citri*) adults, nymphs, and eggs. The combined treatment was significantly more effective; it was observed that the eggs were more tolerant than the nymphs and adults. In pineapples, a mixed treatment of EF + PH3 achieved complete control of eggs at concentrations of 25.1/1.0 (EF/PH3) mg/litre at 8°C with a 4 h exposure time. This combined treatment could offer shorter exposure times and less damage to perishable commodities at low temperatures and could potentially be extended to controlling other quarantine pests of fruit and vegetables for which MB is currently used. Further research (Lee *et al*., 2016) investigated synergistic effect between EF and PH3 for control of cotton aphid, *Aphis gossypii* in quarantine and pre-shipment treatments with encouraging results.

The codling moth, *Cydia pomonella* (CM), is a pest of quarantine concern on apple exports to Asian markets. Apples exported to Japan must be fumigated with MB and then cold stored. Jamieson *et al.* (2016) investigated EF as an alternative to MB, to control CM by determining the responses of key insect stages without fruit and inside apples. Trials without fruit in a 2 h fumigation showed that late-stage CM eggs and third instar CM larvae were the most tolerant life stages, requiring a mean concentration of 1.34–1.94% EF to achieve 99% mortality, but 100% mortality of 4th/5th instar CM larvae. Trials with CM in fruit in a 2 h fumigation showed that treatment with 1.13% EF resulted in 53.4% mortality of 4th/5th CM larvae inside apples. Increasing the mean concentration to 2.4% EF increased the mortality of 4th/5th larvae inside apples to 85.2%.

Jamieson (2015) examined the tolerances of different life stages of tomato potato psyllid (TPP) to EF, finding that eggs were considerably more tolerant than adults and nymphs. Complete elimination of egg hatch was achieved after one hour of exposure to 1.19 % EF. In contrast, all nymphs and adults were killed after a 1-h exposure to 0.12 % and 0.06 % EF, respectively. Assessment of egg mortality was altered to better reflect the post-hatch treatment effects on nymph survival. In a subsequent egg age tolerance trial, mean lethal concentrations for 99 % mortality ranged from ca 1 % EF for young and older eggs to ca 1.5% EF for mid-aged eggs.

Additional successful results with EF include control of eucalyptus weevils, *Gonipterus platensis* Marelli on Pink Lady apples exported from Australia (Argawal, 2015) and control of long-tailed mealybug *Pseudococcus longispinus*, and citrus mealybug, *Planococcus citri* in Australian table grapes and grapefruits, that require MB fumigation but where phytotoxicity and reduced shelf life make MB treatment unattractive (Lima, 2015). Pannasee et al. (2015) conducted fumigations with EF and CO_2 for 2.5 hours in export cartons in simulated cool down from 15°C to 10°C were found to control mealybugs without damaging the produce. Insects hiding in longkong (*Aglaia dookoo* Griff.) clusters caused a serious problem in exporting the fruit. EF at 75 g/m3 for 6 hours completely eradicated black ants, *Technomyrmex* sp., and mealybug, *Exallomochlus hispidus*. EF at 25 g/m3 in combination with 50% CO_2 was also found to completely eradicate the black ant and the mealybug. However, the combined treatment reduced the effect of 1-MCP in controlling postharvest fruit abscission.

Vapormate was also evaluated in South Africa by Grout and Stoltz (2016) who reported that fruit is sometimes rejected for export due to the presence of live arthropods that are not considered pests of the fruit concerned. They fumigated *Macchiademus diplopterus* at a dosage of Vapormate 250 g/m^3 for 4 h resulting in complete control. A small-scale trial using the same ethyl formate treatment also killed the arboreal mite, *Siculobata sicula*. The treatment conditions did not appear to have phytotoxic effects on pears or oranges unless they had prior mechanical injuries.

Further good results with EF fumigation have been reported by Bessi et al. (2016) on dates of the Deglet Nour variety, once treated with MB and even receiving special exemption from phase-out for several years. Also by Agarwal *et al*., (2015) for controlling citrus mealybugs, adults of the Californian red scale and all stages of Fuller's rose weevil. Eucalyptus weevils attacking Pink Lady apples did not survive a 24 h treatment with 30 g/m^3 of EF at 25°C or 50 g/m^3 at 4-8°C.

Efficacy of EF and MB were compared for disinfestation of the citrus mealybug *Planococcus citri* (Hemiptera: Pseudococcidae) on bananas imported into South Korea (Park et al., 2020). Results showed that EF fumigation sorption to bananas and packaging materials lowered the realized EF concentrations around banana and reduced the mortality of *P. citri* eggs despite similar efficacy of MB and EF. Cho *et al*. (2020) evaluated the combined effect of EF (20 g/m^3) plus PH_3 (1 g/m^3) on mealybugs affecting nursery plants, but despite good control some phytotoxicty occurred.

EF was also recently evaluated as a potential MB alternative for controlling exotic ants and termites from stone and lumber imported into Korea with promising results. Commercial-scale trials suggest that EF fumigation may be applicable for disinfestation of invasive worker ants and female alates of *Soleopsis invicta* on imported lumber (Kim *et al*., 2021).

The brown marmorated stink bug (BMSB), *Halyomorpha halys* (Hemiptera: Pentatomidae), is a sap sucking insect native to China, Japan and Korea that has become invasive in North America, Europe and Chile. It causes significant damage to a wide array of economically important crop species.
New Zealand has adopted EF (with CO_2) for control of these ants and the brown marmorated stick bug as approved biosecurity treatments (see table 5-3).

Kwon et al. (2021a) explored the potential of using stand-alone EF treatment and a combined treatment of EF and cold temperature for controlling spotted wing drosophila, *Drosophila suzukii* (Diptera: Drosophilidae), which has become a major phytosanitary trade barrier in the U.S. and Europe in imported blueberries. In small scale pilot studies, 9-day stand-alone cold treatment at 5°C was sufficient for complete control of *D. suzukii* eggs and larvae tested, but not pupae. The efficacy of this cold treatment appeared to improve when *D. suzukii* eggs were first treated with low-dose EF (L(ct)50% level) prior to the cold treatment.

Kim *et al*. (2021) attempted to shorten phosphine treatment time and avoid resistance to this fumigant with a combined treatment with EF for control of *Planococcus citri*. The efficacy of PH_3 decreased after reducing the treatment time, but synergistic effects were observed at all stages of development of *P. citri* when both fumigants were used simultaneously for 4 h.

Similarly, Kwon *et al*. (2021b) evaluated the efficacy of EF, PH_3 and the combination of EF + PH_3 on the mushroom fly, *Lycoriella mali* (Diptera: Sciaridae), the primary pest in imported mushrooms in South Korea. The combination treatment had a synergistic effect, with no phytotoxic damage.

South Korea requires treating sweet persimmon and sweet pumpkin before export to control *Tetranychus urticae* and these requirements are currently met successfully with EF and 1-methylcyclopropene or EF alone. Lee *et al*. (2018a; b) demonstrated that the fruit fumigations completely control *T. urticae* on sweet persimmon and adults and eggs of *T. urticae* on sweet pumpkin.

Draslovka registered ethyl formate as eFumeTM (active ingredient 16,7 % ethyl formate, rest CO2). The company mentions the following key points (Hall 2022, pers. comm.):

- Generally regarded as safe (GRAS)
- No maximum residue limit (MRL)
- Short ventilation period
- Significantly improved vaporizer
- Registered for a wide range of commodities and pests in Australia

This company has also developed a vaporiser for a faster transformation of the premixed liquid into the gaseous form and the application of eFumeTM. For application in shipping containers: the company gives the recommendation: Draslovka eFumeTM vaporizer/ 420 g/m^3/ 40 ft shipping container: 68 m^3/ 29 kg product.

In an oral presentation, Matthew Hall presented a table with effective dosages of eFume against various pests on various products.

TABLE 5-9: TARGET COMMODITIES AND EFFECTIVE DOSE RATES TOWARDS VARIOUS ARTHROPOD PESTS OF EFUMETM

Presentation of Dr. M. Hall, 2022; oral presentation during the MBTOC meeting in Bonn in September

Target commodity	Target pests	dose rate in g/m³	treat ment (hr)
cereal grains, oil seeds, dried fruits, dates, tobacco, grain storage premises and equipment	lesser grain borer *Rhyzopertha dominica* (all stages), red flour beetle *Tribolium castaneum*, psocids (various species), storage moths (*Ephestia* spec., *Plodia interpunctella*), saw-toothed grain beetle *Oryzaephilus surinamensis*, flat grain beetle *Cryptolestes pusillus*, cigarette beetle *Lasioderma serricorne* (all stages), dried fruit beetle *Carpophilus hemipterus*, sap beetle *Carpophilus maculatus*, rice weevil, *Sitophilus oryzae*	660 or 420	6 24
banana	mites (*Oligitetranycus* spec.), mealybugs (*Dysmicoccus* spec.), scales (*Aspidiotus* spp.), coffee bean weevil (*Araecerus fasciulatus*)	420	6
capsicum or sweet pepper	Western flower thrips (*Frankliniella occidentalis*)	70	2
apple	obscure mealybugs (*Pseudococcus viburni*) , Onion thrips (*Thrips tabaci*), Latania scale insects (*Hemibernesia lataniae*)	160	1
pineapple	mites (*Dolichotetranychus floridanus*), mealybugs (*Dysmicoccus neobrevipes*), scale (*Diaspis bromiliae*)	420	2
kiwifruit excluding gold kiwifruit	oleander scale (*Aspidiotus nerii*), long tailed mealybugs (*Pseudococcus longispinus*)	140	6
table grapes blueberries, persimons	light brown apple moth (*Epiphyas postvittana*), red back spider (*Latrodectus hasselti*), two spotted mite (*Tetranychus urticae*) long tailed mealybugs (*Pseudococcus longispinus*), Western flower thrips (*Frankliniella occidentalis*), plague thrips (*Thrips imagines*)	240 120	4 3
citrus	light brown apple moth (*Epiphyas postvittana*), Fuller's rose weevil (*Asynonychus cervinus*), Californian red scale (*Aonidiella aurantia*), bean thrips (*Caliothrips fasciatus*) long tailed mealybugs (*Pseudococcus longispinus*), citrus mealybug (*Planococcus citri*)	360 330	6 3
Fresh sweet corn	Cotton bollworm or corn ear worm (*Helicoverpa armigera*), native budworm or Australian bollworm (*Helicoverpa punctigera*), two spotted mite (*Tetranychus urticae*), Western flower thrips (*Frankliniella occidentalis*), plague thrips (*Thrips imagines*), green peach aphid (*Myzus persicae*), corn aphid (*Rhopalosiphum maydis*)	270	4
Bed bugs	Bed bugs adults, immature and egg stages (C*imex lectularius*)	510	4

5.9.4.4. Methyl iodide (CH_3I)

In Japan, methyl iodide is still under study as a potential fumigant for controlling aphids, *Aphis craccivora*, *Myzus persicae*, mealybug, *Planococcus citri*, mites *Tetranychus urticae; T, kanzawai*, and thrips *Frankliniella intonsa; Thrips tabaci*, on fresh fruit and vegetables.

Dosages of 20 g/m³ to 30 g/m³ for 2 h at 10°C or higher and 40 g/m³ to 61 g/m3 for 3 h at 10°C or higher were recommended to control those insect pests as quarantine treatment schedules (Naito *et al*., 2014, 2015).

For controlling granary weevil, *Sitophilus granarius*, susceptibilities of pupa and adult stages were investigated in fumigated with methyl iodide for 24 h at 15°C and found that pupal stage was seemed to be less susceptible than adult. Under 24 h fumigation, dosages of 2.0 mg/l to 3.5 mg/l were required to kill all individuals of pupal stage tested at 10°C to 20°C, and fumigations with dosages of 1.6 mg/l to 2.8 mg/l at 10°C to 20°C were able to kill all individuals of adult stage (Nishizaki *et al*., 2017).

5.9.4.5. Phosphine (PH_3)

Indonesia has projects for replacing MB used for QPS (reported usage is nearly 100 tons per year) with the phosphine + CO_2 mix known as ECO2FUME®. This is used to treat exported woodchips as well as coffee, cocoa beans and other exported commodities requiring QPS treatments (Tumambing, 2013). Indonesia has developed a QPS phosphine fumigation protocol manual (Salazar, 2014).

ECO2FUME® is registered in Morocco (ONSSA, 2015) for grain fumigation. In Turkey, ECO2FUME® efficacy trials have been conducted to establish QPS fumigation protocols for export cut flowers (carnation, gerbera and roses) against thrips (*Frankliniella occidentalis*) and mites (*Tetranychus cinnabarinus*) at 4°C. Trials with ECO2FUME® for dried fruits have been also conducted to control saw-toothed grain beetle, *Oryzaephilus surinamensis*, and raisin moth, *Ephestia figulilella*, where 100% mortality of all stages of these pests was achieved using 1000 ppm PH_3 (70 g ECO2FUME®/m^3) for 24 h at 23°C or higher (Salazar 2014). In Korea, efficacy trials with ECO2FUME® have been conducted to control eggs and adults of various insects on strawberries (1,100 ppm, 24 h, 2°C or 600 ppm, 24 h, 10°C), cherry and tomato (25 ppm, 24 h, 13°C), paprika (30 ppm, 24 h, 13°C), cut flowers (1,400 ppm, 24 h, 8°C) and nursery trees (1,400 ppm, 48 h, 15°C) (Salazar 2014). Phosphine fumigation at 4 g/m^3 for 1 h was sufficient to obtain 100% mortality of the second instar larvae of thrips (Deewatthanawong et al., 2017). The results demonstrated that phosphine fumigation showed great potential for quarantine treatment of orchid cut-flowers.

Japanese import plant quarantine regulations require consignments where live specimens of the granary weevil, *Sitophilus granarius*, are detected to be fumigated with MB, and this is the only fumigant specified for such events. Fumigation with PH_3 is not permitted, as its efficacy against pupal stages of *Sitophilus* spp. was reported as low (Mori and Kawamoto, 1966). Research aimed at reducing MB use for this QPS application has been conducted, to determine a PH_3 fumigation standard to kill *S. granarius* considering treatment conditions, sorption onto stored grains and preliminary mortality tests, that could lead to an appropriate treatment schedule (Ishige *et al*., 2017). Mortality tests showed complete kill of *S. granarius* at a dose of 2.0 mg/l with a loading factor of 0.5 kg/l or below for 24 days at 10°C to 15°C, for 16 days at 15°C to 20°C, for 7 days at 20°C to 25°C and for 5 days at 25°C to 35°C. Negative effects were not found. Nishizaki *et al*. (2016) studied the survival of *S. granarius* on grain and beans treated with PH_3. They examined twelve different products (corncob meal, corn gluten feed, cotton-seed, flax-seed, rapeseed, rapeseed meal, safflower seed, sesame seed, sorghum, soybean, soybean meal and wheat-bran pellets) and found that a new generation of adults occurred in wheat-bran pellets and sorghum, but not in other materials. The pest also survived in impurities from corncob meal, flax seed and safflower seed. The study further showed that in a single generation of *S. granarius* adults survived more than 40 days on wheat-bran pellets and sorghum, but only 20 days or less on the 10 remaining grains or foodstuffs.

In Thailand, all orchid cut-flowers are normally fumigated with MB for postharvest control of thrips before export. Seeking MB alternatives, Deewattnanawong *et al*. (2017) found no damage to orchid cut-flowers (Dendrobium Sonia 'No. 17') fumigated with PH_3 at a dosage of 4 g/m^3 for 1 hour, and this was led to 100% mortality of second instar thrips larvae. Phosphine is also used to treat Colombian cut flowers before export to the USA, and this has resulted in a substantial decrease of interceptions by phytosanitary authorities and in consequence to mreduced fumigations with MB at the incoming border (ASOCOLFLORES, pers. comm. 2021)

Kim *et al*. (2015) investigated the effect of PH_3 and the synergistic effect of PH_3 under controlled atmospheres of 50 and 80% oxygen respectively, to all developmental stages of the potato tuber moth, *Phthorimaea operculella*, and found that the larval stage was the most susceptible to PH_3 at both 5°C and 20°C. All the developmental stages showed greater susceptibility to PH_3 at 20°C than at 5°C, whereas the susceptibility of adults was not affected by the temperature. The atmospheric oxidation of PH_3 increased the toxicity of fumigation toward all developmental stages at both temperatures.

Liu (2015) subjected the light brown apple moth, *Epiphyas postvittana* (Walker), eggs to oxygenated phosphine fumigation treatments under 70% oxygen on cut flowers of roses, lilies, tulips, gerbera daisy, and pompon chrysanthemums to determine efficacy and safety. Flowers were fumigated separately by species with 2,500 ppm phosphine for 72 h at 5°C. Egg mortalities of 99.7 to 100% were achieved across cut flower types but gerbera daisies showed damage. A 96-h fumigation with 2,200 ppm phosphine of eggs on chrysanthemums cut flowers did not achieve complete control of light brown apple moth eggs. A simulation of fumigation in hermetically sealed fumigation chambers with gerbera daisy showed significant accumulations of carbon dioxide and ethylene by the end of 72 h sealing. However, oxygenated phosphine fumigations with carbon dioxide and ethylene absorbents did not reduce the injury to gerbera daisy, indicating that it is likely that phosphine may directly cause the observed injury. Oxygenated phosphine fumigation is effective against light brown apple moth eggs. but may not be able to achieve the required probit 9 quarantine control level.

Recent research continues to support use of phosphine as an alternative to MB for stored grain. Sri Lanka and Pakistan are increasingly accepting PH_3 to replace MB on imported grains (Mirage News, 2022). In Japan, a newly developed method for applying aluminum phosphide that prevents residual powder on treated grain and substantially saving labor is now registered. Sachets, of dosed formulation from which phosphine gas is generated and evenly circulated are hung above the grain layer. When the fumigation is over sachets are removed from the silo and disposed safely (Soma *et al.*, 2018).

Most studies with phosphine gas highlight eggs as the most tolerant stage. Recently Gourgouta *et al.* (2021) conducted mortality tests on different life stages of the khapra beetle (*T. graniarum)* including diapause larva, with phosphine at dosages of 50, 100, 200, 300, 500 and 1,000 ppm, for three days. They found that although eggs are the most tolerant to phosphine, 100% were killed with 1,000 ppm of phosphine after 3 days of exposure.

Resistance to phosphine

MBTOC notes as in previous reports that resistance to phosphine (PH_3) has been recorded in storage pests around the world (Opit *et al.*, 2012; Jagadeesan *et al.*, 2012). Recent surveys in major grain-growing countries confirm this ongoing concern for PH3 resistance, as grain is stored everywhere and resistant insects survive poor fumigations (Collins *et al.*, 2017). On the other hand, there is information available on relatively easy testing for resistance prior to fumigation and adjusting the dosage of phosphine according to the finding. Even resistant stages and species of insect pests can effectively be controlled with elevated dosages of this gas. Often enough, the occurrence of resistance is caused by use of too short exposure time (weeks are recommended instead of days) and too small amounts of phosphine in the first place. At higher temperatures than 20°C, the dosages may be appropriately reduced without losing the high degree of control compared with efficacy data and necessary dosages at lower temperatures. This information has been published over the last decades in many articles but practitioners are often under economic pressure to use sublethal fumigation conditions. In the light of the scarcity of effective pest control agents - and now the additional threat to lose access to sulfuryl fluoride as a fumigant for pest control, MBTOC expresses its concern on this topic and encourages the proper use of phosphine to avoid the risk of selection of resistant insect strains and keep this gas available for pest control.

The majority of susceptible populations of insect species are quickly immobilized by phosphine even in the shortest exposure period (15 min); however, resistant populations that were active even after 300 min. This finding was first reported by Reichmuth in 1991 and developed into a quick test for resistance prior to fumigation. 15 minutes observation time of a group of several insects from an infested object at about 1000 ppm phosphine in air, for instance within a large transparent syringe of 100 ml, was recommended for this test to distinguish between susceptible and resistant strains of moving stages.

The degree of delay of occurrence of narcosis could be related to the degree of resistance and the dosage (concentration and exposure time) could be adapted appropriately. A thesis from Oklahoma (Cato, 2015) dealt in detail with this finding and several authors confirmed the practical advantage. Additional bioassays showed the presence of the "sweet spot", i.e., decrease of mortality with the increase of concentration. For most of the tested species, the "sweet spot" appeared in 1000 ppm and 2000 ppm, respectively, after a 5 h exposure time, regardless of the level of resistance to phosphine. Temperature was also observed as being important. The results are particularly relevant in terms of the assessment of resistance and in the context of non-linear recovery at elevated concentrations, indicating the occurrence of strong hermetic reversals in phosphine efficacy.

Combined fumigation with reduced rates of phosphine together with sulfuryl fluoride controlled highly resistant rusty grain beetles *Cryptolestes ferrugineus* (Coleoptera: Laemophloeidae) (Jagadeesena *et al*, 2021). Aulicky et al. (2019) validated the efficacy of phosphine also on resistant strains of *Sitophilus granarius* and *Tribolium castaneum* from the Czech Republic.

Horn and Horn (2004, 2006), Horn *et al*. (2005), and Horn (2012) demonstrated the possibilities of implementing phosphine into the treatment of fresh fruit at low temperatures against quarantine organisms, for instance prior to exportation from Chile into the US. Fumigation with PH_3 at low temperatures completely killed the oriental fruit fly, *Bactrocera dorsalis*, which is a quarantine pest of Chinese loquat, *Eriobotrya japonica*, with no adverse effects on fruit quality (Liu *et al*., 2018).

Fresh citrus exports from the United States may be subject to postharvest phytosanitary treatment. Obenland *et al*. (2021) compared phytotoxic response and damage of the fruits fumigated by phosphine and methyl bromide with assuming oceanic voyage of 28 days followed by 2 weeks to typify distribution and marketing conditions. Pre-departure phosphine fumigations with 1.5mg/l for 12 or 48 hours at 5°C or for 48 h at 12°C did not alter marketability of sensory quality of fruits for any of the citrus types while arrival MB fumigation with 64 mg/l for 2 h at 5°C damaging to the peel of all citrus, except Valencia oranges, and harmed grapefruit and mandarin flavor.

Phosphine and SF successfully eliminated pinewood nematodes on pine wood chips but neither were completely effective on pine blocks with intact bark.

5.9.4.6. Sulfuryl fluoride (SO_2F_2, SF, Vikane^{TM}, Profume^{TM})

SF has long been shown to penetrate wood as effectively as MB and is also known to have a great potential for controlling forest pest insects; it is considered suitable for fumigation of exported logs. As such it has been implemented into the recommendations for a range of phytosanitary treatments in quarantine (ISPM 15, 2018; ISPM 28, 2017).

Sulfuryl fluoride was determined to be a suitable quarantine treatment fumigant against the khapra beetle *Trogoderma granarium* (Ghimire *et al*., 2015). Recently, Myers et al. (2021) have evaluated a treatment for khapra beetle, Trogoderma granarium, using a combination SF and propylene oxide (PPO).

In 2018 the use of SF for control of insects and nematodes in debarked wood was approved as a treatment for wood packaging in trade under ISPM 15. The ISPM 15 standard had approved treatments besides MB fumigation before 2018 (heat treatment), however limitations to their adoption may exist, for example the need of electric power supply or temperature control devices. The approval of SF as another chemical option provides a new tool for compliance with ISPM 15. There are two schedules of sulfuryl fluoride treatment in ISPM 15 which prescribe a minimum required ct (gh/m^3) to be 1,400 gh/m^3 for 24 h and 3,000 gh/m^3 for 48 h at 30°C or above and at 20°C or above, respectively. More details are listed under the section on IPPC below.

SF is also used at a low dose of 24g/m^3 (CT 200 g/m^3) in the United States and Europe as a quarantine treatment on cargo at risk of carrying the brown marmorated stink bug, *Halyomorpha halys*, to

Australia and New Zealand. It is approved for export logs to China from Australia and used on European logs to China (Reichmuth, pers. comm., 2022).

SF has been shown to penetrate wood as effectively as MB (Ren *et al.*, 2011). Its efficacy was demonstrated against *Hylotrupes bajalus* in the timber parts of a historic building in Istanbul (Yildirim *et al.*, 2012).

SF is also known to have a great potential for controlling forest pest insects (Soma *et al.*, 1996, 1997), and is considered suitable for fumigation of exported logs (Zhang 2006). As such it has been implemented into the recommendations for a range of phytosanitary treatments in quarantine (ISPM 15 2018, ISPM 28 2017) against the pinewood nematode, *Bursaphelenchus xylophilus* (Dwinell *et al.*, 2005; Soma *et al.*, 2001; Sousa *et al.*, 2010, 2011).

The use of SF as a gas for pest control may be limited in the future due to its high global warming potential (Vassileios et al., 2008, Mühle et al., 2009). MBTOC has expressed concern that many of the former fields of application of MB where SF has taken its place will remain without viable alternative when SF might not be available in the future.

5.9.4.7. Nitric oxide (NO)

NO is considered as an alternative to MB for postharvest pest control on lettuce, particularly the currat-lettuce aphid *Nasonovia ribisnigri* (Hemiptera: Aphididae) and western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae) (Yang and Liu, 2019).

Liu and Simmons (2021) demonstrated that NO fumigation was effective against all life stages of the light brown apple moth, *Epiphyas postvittana* (Lepidoptera: Tortricidae). NO was further shown to be effective against navel orangeworm, *Amyelois transitella* (Lepidoptera: Pyralidae), although timing and application rates were variable depending upon the life stage to be treated (Yang *et al.*, 2021). Eggs were more tolerant to NO than larvae and pupae. NO is considered as an alternative to MB for postharvest pest control on lettuce, particularly the aphid, *Nasonovia ribisnigri*, and western flower thrips, *Frankliniella occidentalis* (Yang and Liu, 2019).

5.9.4.8 Controlled atmospheres (CA) treatments

Controlled atmospheres (with low content of oxygen and increased content of CO_2 and/or nitrogen) combined with low temperature are increasingly used and accepted as quarantine treatments, often with good potential to replace MB. Annis (1987), Calderon and Barkai-Golan (1990), Adler *et al.*, (2000), among many other authors - before and after them-, have presented very valuable information on the wide uses of these atmospheres with low residual oxygen content.

The schedule for import treatment (e.g., rice) from countries with established occurrence of the khapra beetle to Australia using CA is published and can be downloaded (DAFF, 2021). A controlled atmosphere system that uses nitrogen to lower O_2 levels below 1% combined with high temperatures (38 C) is being used commercially in Indonesia for commodities such as tobacco (exposure time 4 days). It can also be used on grains with good results. Forty-six similar facilities are reported in 18 countries (Mahmudi, 2014).

Adoption of controlled and modified atmospheres (low oxygen) with or without warm to high temperature is increasing, and can be used in many applications, from stored grain and other commodities to treating ship holds, and aircraft (ECO_2, 2016)

In Vietnam, a continuous in-line CA treatment process, which takes only 40 minutes kills insects attacking dry commodities in all stages of their development (Cattis, 2020). The treatment is conducted within a compartment at 55-70°C (depending on the product) and an atmospheric environment with very low oxygen content, where the product is dropped in and any insects present are controlled within 30 min. A conveyor belt takes the product subsequently to a second compartment at 15 to 25°C where it is cooled down to ambient temperatures by mechanical means. The cooling process also enables moisture control of the product. The system works with a heat pump and cooling system, with high energy efficiency and is currently commercially operated for treating nuts (e.g. cashew nuts) and more recently various types of beans (Cattis, 2022). Trials are under way for dried fruit products and fresh fruit.

Patil *et al*. (2019) reported a novel cold-quarantine treatment for mango quarantine pests combining cold storage at 2ºC with artificial ripening with 150 ppm ethylene and modified atmosphere (fruit enclosed in perforated bags), resulting in significantly reduced chilling injury and ensuring consumer acceptance (taste, aroma and texture).

Hot water treatment combined with high-pressure controls taro mite, *Rhixoglyphus* sp., and root knot nematodes, *Meloidogyne* spp.) (Jamieson, 2018). Douda et al. (2021) investigated the using ethane dinitrile during soil fumigation against *Meloidogyne hapla* and determined carrot yield parameters. Control of mango quarantine pests is based mainly on cold treatments, with a possible deterioration of fruit quality.

Tuta absoluta, an invasive and increasingly troublesome pest species affecting tomatoes, other solanaceous species and many other crops, which limits exports in various countries, is effectively controlled with modified atmospheres and cold treatments. Exposure of *T. absoluta* to modified atmospheres with 40% CO_2 at 25ºC for 72 h was effective for controlling all life stages. In addition, a cold storage treatment at 1ºC for 10 days also proved effective for egg control (Riudavets *et al*., 2016). These two treatments showed no negative effects on the quality of the tomatoes. See Annex 3 for comprehensive information on lethal conditions to control various species and developmental stages of pest insects (Reichmuth, 2000).

5.9.5. Reducing emissions and improving efficiency of MB treatments

Nearly all the MB used for QPS uses is emitted to the atmosphere although adoption of recapture systems is slowly increasing. Implementation of recapture systems however, is mainly associated to human safety concerns outside of Montreal Protocol regulations. Despite the ability of recapture systems being available for MB they are not widely used as they are more costly compared to venting directly to the atmosphere or impractical for all uses. Nevertheless, the company Nordiko reported that their recapture systems are now in 30 countries and they estimate that their systems have capacity to capture about 500 tonnes MB/year in total worldwide (Nordiko, 2014).

The New Zealand EPA required half of all under cover QPS MB fumigations to be carried out using recapture equipment from January 2021 and all fumigations from January 2025. From 1 January 2023, 80 percent of methyl bromide will need to be recaptured from every container fumigation, increasing to 99 percent recapture from 1 January 2031. However, four major ports have fully adopted it early. A locally based company attempted to develop a recapture system large enough to deal with ship hold fumigations but did not succeed and hence ship hold fumigation with MB has been banned from the start of 2023 (NZ EPA, 2020).

In addition, efforts have been made since many years to reduce the amounts of MB required for phytosanitary actions for trade, reduce ineffective practices and retreatment. Examples of this are the Australian Fumigation Accreditation Scheme (AFAS) and the International Cargo Cooperative in Biosecurity Arrangement (ICCBA). AFAS is a programme comprising 600 fumigation companies in nine countries, and which was developed for products exported to Australia has resulted in a 50% reduction in detected fumigation failures requiring re-fumigation on arrival into Australia, therefore saving MB. The scheme is being further developed under the new International Cargo Cooperative Biosecurity Arrangement to include trade between additional countries. The ICCBA also developed standardized methods for heat treatment of export commodities and proper storage conditions thereafter (Cox, 2014).

A research program was put in place to develop a new protocol for the export of Australian capsicums to New Zealand, which are currently exported with MB fumigation at a dose of 40g m3 for 2 h at 17°C. This treatment however resulted in reduced fruit quality. Wyatt (2015) investigated the efficacy of fumigating with lower concentrations of MB applied over longer treatment times with the aim of determining a dose efficacious against fruit flies and within the tolerances of the fruit. Capsicums, *Capsicum annuum*, were fumigated with MB at a dose of 18 g/m^3 at 18°C for 5 h as a quarantine disinfestation treatment against Queensland fruit fly, *Bactrocera tryoni* (Diptera: Tephritidae). Three large scale trials were conducted against each of the four immature life stages, eggs, first, second and third instars. There were no survivors, resulting in an efficacy of >99.99% mortality at the 95% confidence level for each life stage.

In the same set of trials, commercial fruit were fumigated under the same conditions and then held at 6°C for 16 days or 6°C for 10 days followed by 10°C for 6 days. This simulated transport at 6°C followed by retail display at 10°C. Fruit quality parameters of weight loss, total soluble solids and external quality including, visual appearance, skin wrinkling, skin pitting, and incidence and severity of rots were assessed with no significant adverse treatment effects present.

The new protocol uses roughly half the concentration of fumigant but applied for double the treatment time to maintain the efficacy against Queensland fruit fly, a significant quarantine pest in Australia. Whilst the reduction in MB used is environmentally beneficial, the research was instigated to improve out-turn quality of the treated capsicums. The existing protocol for capsicum impacts fruit quality while the lower dose tested in our research had no significant effects on the range of fruit quality attributes tested.

Subsequent research in nectarines and peaches achieved complete mortality of all life stages with a dose of 18 g/m^3 methyl bromide at 18°C for 5.5 h and has resulted in a new protocol for the export of Australian nectarines to China. The research has now been extended to develop low-dose fumigation schedules for apple, pear, table grape, mango, plum, strawberry and citrus.

5.10. Changes in fumigation regulations for imported goods

India used to fumigate imported goods with MB on arrival but is now imposing a rule whereby these will need to be treated at the origin before export. This rule impacted for example teak log exports from Latin American countries, or exports of pulses from Canada, where MB use is minimal or no longer exists, even for QPS.

Ecuador has come to a bilateral agreement with India whereby Indian authorities have accepted pre-shipment fumigation of teak logs with 3g/m3 of phosphine gas (aluminium phosphide/ magnesium phosphide of 56% or more pure substance with rest additives, 3 tablets/m^3) for 7 days. Ecuadorian fumigators conducting the treatment must be accredited by the Indian NPPO, which takes place through a direct technical visit (India Min of Agric., 2017).

Canada has sought exemption from the requirement to fumigate with MB due to its ODP and also because it has been deemed to be ineffective at low temperatures. A careful and comprehensive systems approach is currently under negotiation (Farms.com newsletters, 2022)

A systems approach is now also being implemented for controlling Pests of Korean Concern associated with Chilean Blueberry (http://www.sag.cl/sites/default/files/plant_quarantine_import_requirements_for_fresh_fruits_of_blueberry_from_chile_20170623.pdf)

5.11. International Plant Protection Convention (IPPC)

With the aid of the Ozone Secretariat, MBTOC has taken steps to reactivate the Memorandum of Understanding (MOU) between the Ozone Secretariat and the International Plant Protection

Convention (IPPC), which was drawn in 2012 to “Promote and facilitate collaboration between the Montreal Protocol and the IPPC through joint participation of technical experts in the technical panels and committees of both treaties, such as the Methyl Bromide Technical Options Committee, the Technical Panel on Phytosanitary Treatments (TPPT) and the Expert Working Group on Alternatives to Methyl Bromide, to enhance communication and advice consistent with the aims of both agreements.”On the basis of MOU, MBTOC maintains regular communication with relevant bodies of IPPC dealing with phytosanitary measures and standards where MB is of interest.

The IPPC has now approved and published 26 international approved treatments in recent years for use on a combination of fresh produce, wood or pest specific treatments through the work of the TPPT.

MBTOC keeps track of efforts made by IPPC and its subsidiary bodies to replace MB use for quarantine purposes as far as possible without losing the high degree of control in the various fields of application. Table 5-2 gives an impression of the magnitude of the task of finding efficacious and economically feasible alternatives for MB-treatments for quarantine. Treatments can take three to nine years to progress through to approval depending on the quality of the data presented. Once approved it allows international trade to occur for that pest and or commodity combination.

The full list and descriptions of the treatments are available at: https://www.ippc.int/en/core-activities/standards-setting/ispms/

The TPPT evaluates data submissions from NPPOs and RPPOs and reviews, revises and develops phytosanitary treatments. It further provides guidance to the Standards Committee (SC) regarding specific phytosanitary treatment issues. The TPPT evaluates treatment submissions against ISPM requirements. Their reports are available under: https://www.ippc.int/en/core-activities/standards-setting/expert-drafting-groups/technical-panels/technical-panel-phytosanitary-treatments/

Other lists of quarantine treatments are available at:
https://www.eppo.int/RESOURCES/eppo_standards/pm10_phytosanitary_treatments
https://www.aphis.usda.gov/import_export/plants/manuals/ports/downloads/treatment.pdf
https://www.mpi.govt.nz/.../1555-approved-biosecurity-treatments-for-risk-goods
http://www.pps.go.jp/english/law/list2-2.html
http://www.inspection.gc.ca/plants/horticulture/imports/treatment-schedules/eng/1501526269211/1501526560731

The IPPC Standards committee has two quarantine treatment related documents out for consultation:

- 2018 Second Consultation: Draft ISPM: Requirements for the use of fumigation as a phytosanitary measure
- 2018 First Consultation: Draft ISPM: Requirements for the use of modified atmosphere treatments as phytosanitary measures

TABLE 5-10 ALTERNATIVE TREATMENTS APPROVED BY FOR COMPLIANCE WITH ISPM STANDARDS

ISPM 28 number	Type of Treatment	Pest	Product Commodity	Schedule
PT 01	Radiation treatment (RAT)	*Anastrepha ludens* Tephritidae : Diptera Mexican fruit fly ANSTLU	All fruits and vegetables, that are hosts of *Anastrepha ludens*	Minimum absorbed dose of 70 Gy to prevent the emergence of adults of *Anastrepha ludens*.
PT 02	Radiation treatment (RAT)	*Anastrepha obliqua* Tephritidae : Diptera Antillean fruit fly ANSTOB	All fruits and vegetables that are hosts of *Anastrepha obliqua*	Minimum absorbed dose of 70 Gy to prevent the emergence of adults of *Anastrepha obliqua.*

PT 03	Radiation treatment (RAT)	*Anastrepha serpentina* Tephritidae : Diptera sapodilla fruit fly ANSTSE	All fruits and vegetables that are hosts of *Anastrepha serpentina*	Minimum absorbed dose of 100 Gy to prevent the emergence of adults of *Anastrepha serpentina*.
PT 04	Radiation treatment (RAT)	*Bactrocera jarvisi* Tephritidae : Diptera Jarvis's fruit fly BCTRJA	All fruits and vegetables that are hosts of *Bactrocera jarvisi*	Minimum absorbed dose of 100 Gy to prevent the emergence of adults of *Bactrocera jarvisi*.
PT 05	Radiation treatment (RAT)	*Bactrocera tryoni* Tephritidae : Diptera Queensland fruit fly DACUTR	All fruits and vegetables that are hosts of *Bactrocera tryoni*	Minimum absorbed dose of 100 Gy to prevent the emergence of *Bactrocera tryoni* adults.
PT 06	Radiation treatment (RAT)	*Cydia pomonella* Tortricidae : Lepidoptera codling moth CARPPO	All fruits and vegetables that are hosts of *Cydia pomonella*	Minimum absorbed dose of 200 Gy to prevent the emergence of adults of *Cydia pomonella*.
PT 07	Radiation treatment (RAT)	Tephritidae Insecta : Hexapoda 1TEPHF	All fruits and vegetables that are hosts of fruit flies of the family Tephritidae	Minimum absorbed dose of 150 Gy to prevent the emergence of fruit fly adults.
PT 08	Radiation treatment (RAT)	*Rhagoletis pomonella* Tephritidae : Diptera apple maggot fly RHAGPO	All fruits and vegetables that are hosts of *Rhagoletis pomonella*	Minimum absorbed dose of 60 Gy to prevent the development of phanerocephalic pupae of *Rhagoletis pomonella*.
PT 09	Radiation treatment (RAT)	*Conotrachelus nenuphar* Curculionidae : Coleoptera plum weevil CONHNE	All fruits and vegetables that are hosts of *Conotrachelus nenupharl*	Minimum absorbed dose of 92 Gy to prevent the reproduction in adults of *Conotrachelus nenuphar*.
PT 10	Radiation treatment (RAT)	*Grapholita molesta* Tortricidae : Lepidoptera oriental fruit moth LASPMO	All fruits and vegetables that are hosts of *Grapholita molesta*	Minimum absorbed dose of 232 Gy to prevent the emergence of *Grapholita molesta* adults.
PT 11	Radiation treatment (RAT)	*Grapholita molesta* Tortricidae : Lepidoptera oriental fruit moth LASPMO	All fruits and vegetables that are hosts of *Grapholita molesta* under hypoxia	Minimum absorbed dose of 232 Gy to prevent oviposition of *Grapholita molesta*.
PT 12	Radiation treatment (RAT)	*Cylas formicarius* Apionidae : Coleoptera sweet-potato weevil CYLAFO	All fruits and vegetables that are hosts of *Cylas formicarius*	Minimum absorbed dose of 165 Gy to prevent the development of F1 adults of *Cylas formicarius*.
PT 13	Radiation treatment (RAT)	*Euscepes postfasciatus* Curculionidae : Coleoptera West Indian sweet-potato weevil EUSPPO	All fruits and vegetables that are hosts of *Euscepes postfasciatus*.	Minimum absorbed dose of 150 Gy to prevent the development of F1 adults of Euscepes postfasciatus.
PT 14	Radiation treatment (RAT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	All fruits and vegetables that are hosts of *Ceratitis capitata*.	Minimum absorbed dose of 100 Gy to prevent the emergence of adults of *Ceratitis capitata*.
PT 15	Vapour Heat (TPT-VH)	Tephritidae : Diptera melon fly DACUCU	*Cucumis melo var. reticulatus* Cucurbitaceae : Cucurbitales netted melon	Fruit core temperature raised to a minimum of 45 °C in a vapour heat chamber and maintained for 30 min as per ISPM 28 PT 15.

			CUMMR (netted melon)	
PT 16	Cold Treatment (TPT-CT)	*Bactrocera tryoni* Tephritidae : Diptera Queensland fruit fly DACUTR	(Orange)	Maximum fruit core temperature kept at 3 °C or below for 16 continuous days.
PT 17	Cold Treatment (TPT-CT)	*Bactrocera tryoni* Tephritidae : Diptera Queensland fruit fly DACUTR	*Citrus reticulata x C. sinensis* (tangor)	Maximum fruit core temperature kept at 3 °C or below for 16 continuous days.
PT 18/1	Cold Treatment (TPT-CT)	*Bactrocera tryoni* Tephritidae : Diptera Queensland fruit fly DACUTR	*Citrus limon* Rutaceae : Sapindales lemon CIDLI (lemon)	Maximum fruit core temperature kept at 2 °C or below for 14 continuous days.
PT 18/2	Cold Treatment (TPT-CT)	*Bactrocera tryoni* Tephritidae : Diptera Queensland fruit fly DACUTR	*Citrus limon* Rutaceae : Sapindales lemon CIDLI (lemon)	Maximum fruit core temperature kept at 3 °C or below for 14 continuous days.
PT 19	Radiation treatment (RAT)	*Dysmicoccus neobrevipes* Pseudococcidae : Sternorrhyncha gray pineapple mealybug DYSMNE *Planococcus lilacinus* Pseudococcidae : Sternorrhyncha cacao mealybug PLANLI *Planococcus minor* Pseudococcidae : Sternorrhyncha passion vine mealybug PLANMI	All fruits and vegetables that are hosts of the above mealybugs	Minimum absorbed dose of 231 Gy to prevent the reproduction of adult females of Dysmicoccus neobrevipes, *Planococcus lilacinus* and Planococcus minor.
PT 20/1	Radiation treatment (RAT)	*Ostrinia nubilalis* Pyralidae : Lepidoptera European corn borer PYRUNU	All fruits and vegetables that are hosts of *Ostrinia nubilalis*.	Minimum absorbed dose of 289 Gy to prevent F1 development of O. nubilalis.
PT 20/2	Radiation treatment (RAT)	*Ostrinia nubilalis* Pyralidae : Lepidoptera European corn borer PYRUNU	All fruits and vegetables that are hosts of *Ostrinia nubilalis*.	Minimum absorbed dose of 343 Gy to prevent F1 egg hatching of O. nubilalis.
PT 21	Vapour Heat (TPT-VH)	*Bactrocera melanota* Tephritidae : Diptera BCTRME *Bactrocera xanthodes* Tephritidae : Diptera BCTRXA	*Carica papaya* Caricaceae : Brassicales pawpaw CIAPA (papaya)	Fruit core temperature raised to a minimum of 47.5 °C in a forced hot air chamber and maintained for 20 minutes as per ISPM 28 PT 21.
PT 22/1	Fumigation (CHT-FU)	Wood-borne life stages of insects, including *Anoplophora glabripennis* (Coleoptera: Cerambycidae), *Anobium punctatum*	Debarked wood not exceeding 20 cm in cross-section at its smallest dimension and 75% moisture content (dry basis).	Sulphuryl fluoride fumigation to achieve a minimum concentration time product (CT) of 3200 g·h/m3 and minimum concentration of 93 g/m3 at ≥15 °C over 24 hours.

		(Coleoptera: Anobiidae) and *Arhopalus tristis* (Coleoptera: Cerambycidae)		
PT 22/2	Fumigation (CHT-FU)	Wood-borne life stages of insects, including *Anoplophora glabripennis* (Coleoptera: Cerambycidae), *Anobium punctatum* (Coleoptera: Anobiidae) and *Arhopalus tristis* (Coleoptera: Cerambycidae)	Debarked wood not exceeding 20 cm in cross-section at its smallest dimension and 75% moisture content (dry basis).	Sulphuryl fluoride fumigation to achieve a minimum concentration time product (CT) of 2300 g·h/m3 and minimum concentration of 67 g/m3 at ≥20 °C over 24 hours.
22/3	Fumigation (CHT-FU)	Wood-borne life stages of insects, including *Anoplophora glabripennis* (Coleoptera: Cerambycidae), Anobium punctatum (Coleoptera: Anobiidae) and *Arhopalus tristis* (Coleoptera: Cerambycidae)	Debarked wood not exceeding 20 cm in cross-section at its smallest dimension and 75% moisture content (dry basis)	Sulphuryl fluoride fumigation to achieve a minimum concentration time product (CT) of 1500 g·h/m3 and minimum concentration of 44 g/m3 at ≥25 °C over 24 hours.
PT 22/4	Fumigation (CHT-FU)	Wood-borne life stages of insects, including *Anoplophora glabripennis* (Coleoptera: Cerambycidae), *Anobium punctatum* (Coleoptera: Anobiidae) and *Arhopalus tristis* (Coleoptera: Cerambycidae).	Debarked wood not exceeding 20 cm in cross-section at its smallest dimension and 75% moisture content (dry basis).	Sulphuryl fluoride fumigation to achieve a minimum concentration time product (CT) of 1400 g·h/m3 and minimum concentration of 41 g/m3 at ≥30 °C over 24 hours.
PT 23/1	Fumigation (CHT-FU)	Wood-borne life stages of *Bursaphelenchus xylophilus* (Nematoda: Aphelenchoididae) and insects, including *Anoplophora glabripennis* (Coleoptera: Cerambycidae), *Anobium punctatum* (Coleoptera: Anobiidae) and *Arhopalus tristis* (Coleoptera: Cerambycidae).	Debarked wood not exceeding 20 cm in cross-section at its smallest dimension and 75% moisture content (dry basis).	Sulphuryl fluoride fumigation to achieve a minimum concentration time product (CT) of 3000 g·h/m3 and minimum concentration of 29 g/m3 at ≥20 °C over 48 hours.
PT 23/2	Fumigation (CHT-FU)	Wood-borne life stages of *Bursaphelenchus xylophilus* (Nematoda:	Debarked wood not exceeding 20 cm in cross-section at its	Sulphuryl fluoride fumigation to achieve a minimum concentration time product (CT) of 1400 g·h/m3

		Aphelenchoididae) and insects, including *Anoplophora glabripennis* (Coleoptera: Cerambycidae), *Anobium punctatum* (Coleoptera: Anobiidae) and *Arhopalus tristis* (Coleoptera: Cerambycidae).	smallest dimension and 75% moisture content (dry basis).	and minimum concentration of 41 g/m3 at ≥30 °C over 24 hours.
PT 24/1	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus sinensis* Rutaceae : Sapindales sweet orange CIDSI	Maximum fruit core temperature kept at 2 °C or below for 16 continuous days.
PT 24/2	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus sinensis* Rutaceae : Sapindales sweet orange CIDSI	Maximum fruit core temperature kept at 2 °C or below for 18 continuous days.
PT 24/3	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus sinensis* Rutaceae : Sapindales sweet orange CIDSI	Maximum fruit core temperature kept at 3 °C or below for 20 continuous days.
PT 25/1	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus reticulata x Citrus sinensis* (tangerine)	Maximum fruit core temperature kept at 3 °C or below for 20 continuous days.
PT 25/2	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus reticulata x Citrus sinensis* (tangerine)	Maximum fruit core temperature kept at 3 °C or below for 20 continuous days.
PT 26/1	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus limon* Rutaceae : Sapindales lemon CIDLI	Maximum fruit core temperature kept at 2 °C or below for 16 continuous days.
PT 26/2	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus limon* Rutaceae : Sapindales lemon CIDLI	Maximum fruit core temperature kept at 3 °C or below for 18 continuous days.
PT 27/1	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus paradisi* Rutaceae : Sapindales pomelo CIDPA (grapefruit)	Maximum fruit core temperature kept at 2 °C or below for 19 continuous days.
PT 27/2	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus paradisi* Rutaceae : Sapindales pomelo CIDPA	Maximum fruit core temperature kept at 3 °C or below for 23 continuous days.
PT 28	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus reticulata* Rutaceae : Sapindales clementine CIDRE	Maximum fruit core temperature kept at 2 °C or below for 23 continuous days.
PT 29	Cold Treatment (TPT-CT)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Citrus clementina* Rutaceae : Sapindales clementine CIDCL	Maximum fruit core temperature kept at 2 °C or below for 16 continuous days.

PT 30	Vapour Heat (TPT-VH)	*Ceratitis capitata* Tephritidae : Diptera Mediterranean fruit fly CERTCA	*Mangifera indica* Anacardiaceae : Sapindales mango MNGIN	Fruit core temperature raised to a minimum of 46.5 °C in a vapour heat chamber and maintained for 10 minutes as per ISPM 28 PT 30.
PT 31	Vapour Heat (TPT-VH)	*Bactrocera tryoni* Tephritidae : Diptera Queensland fruit fly DACUTR	*Mangifera indica* Anacardiaceae : Sapindales mango MNGIN	Fruit core temperature raised to a minimum of 47 °C in a vapour heat chamber and maintained for 15 minutes as per ISPM 28 PT 31.
PT32	Vapour Heat (TPT-VH)	*Bactrocera dorsalis* Tephritidae : Diptera oriental fruit fly DACUDO	*Carica papaya* Caricaceae : Brassicales pawpaw CIAPA	Fruit core temperature raised to a minimum of 46 °C in a vapour heat chamber and maintained for a minimum of 70 min as per ISPM 28 PT 32.

5.12. Remaining challenges

As MBTOC has stated in other reports, confusion persists in some parties with the correct classification of QPS uses under the definitions of the Protocol. The pre-shipment definition is unique to the Protocol and does not apply to the control of quarantine pests: “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;”

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6

6. Alternatives to Methyl Bromide for Pre-plant Soil Treatment

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6.1 Summary

Since the 2018 Assessment Report, a large number of research and review articles on alternatives to MB have been published, providing Parties with information on their relative effectiveness for a wide range of productive sectors. Over the years, MBTOC has identified chemical (fumigants, non-fumigant and natural pesticides) and non-chemical (biological and physical) alternatives that perform consistently across most regions and sectors. Currently, most single chemical alternatives target specific groups of organisms and none of the currently available fumigants, used alone, offer a completely satisfactory alternative compared to MB. Therefore, combinations of fumigants are generally used to give broad scale treatment comparable to MB.

In recent years, there have been many new practices and technologies evaluated to replace MB, i.e. pesticide-coated plastic mulch and new formulations of fumigants. Site specific soil management, use of steam in the open fields, and chlorine dioxide (ClO_2) granules have been developed and commercially adopted. Soil disinfestation has evolved during the last 60 years from using a single measure (steaming or fumigation) to Integrated Pest Management (IPM). IPM combines various techniques (biological, cultural and physical) to reduce the incidence and severity of soil borne pathogens, to minimize the extent of environmental damage and to reduce the impact of chemical inputs on humans and non-target organisms. Pesticides are used only if they are needed.

Alternatives and combination of alternatives are available for virtually all soils applications and particularly for the remaining MB critical uses, which now only includes Tomato and strawberry fruit crops in Argentina and strawberry runners in Australia and Canada. Despite their efficacy, chemical and some non-chemical alternatives have negative impacts on human health, the environment, and the Sustainable Development Goals (SDGs). Many conventional and widely used soil fumigants have a negative impact on the human health (Calderón *et al*., 2022; O'Malley *et al*., 2005; Stott and Gollapudi, 2010).. Acute and chronic exposure risks may include irritation to the eyes, skin and respiratory system, as well as nausea, vomiting, increased risk of certain cancers, and in extreme cases, death.

Negative effects can also occur in more sustainable systems. For instance, the use of copper in organic agriculture is considered as part of an agricultural production system as an alternative to MB, has some concerns for human health and the environment. This has led to regulatory restrictions on the copper use and prohibition in several European countries.

Another issue of concern for modern production systems is that most mulching films (for example: VIF, LDPE) used in soil disinfestation (for example: chemical fumigants, bio fumigants, solarisation) are single use and can persist in the environment long after their intended use. They are degraded into microplastics, and are then transferred and accumulated in food chains, threatening food security, food safety and human health. It has also been reported that chloropicrin, anaerobic soil disinfestation generates high levels of N_2O and are important sources of N_2O in the atmosphere. Microwave use is being evaluated for soil disinfestation, however it has an extremely high-power level required to generate the necessary microwave energy to control soil borne pathogens and weeds. Therefore, human safety, in addition to environmental health should remain central when proposing effective alternatives to MB and exploring sustainable agriculture.

6.2 Introduction

The first use of methyl bromide (MB) as a soil fumigant occurred simultaneously in France, Australia and the USA (California) in the 1930s. Since its discovery and implementation, MB has been consistently effective for control of nematodes, fungi, insects and weeds and has been used on more than 100 crops worldwide. Its high vapour pressure allows for rapid and thorough distribution through the soil, which enhances its effectiveness as a fumigant and allows for a relatively short plant-back interval, giving growers great flexibility (MBTOC 2018, Gullino *et al.* 2022).

January 1, 2015, marked the phase-out deadline for controlled uses of MB in A5 Parties, ten years after non-A5 Parties. As of that date, controlled uses of MB have been only allowed under the Critical Use Exemption (CUEs). By the end of 2017, official reporting indicated that about 99% of the global consumption baseline (all Parties) for controlled (non-exempt) uses had been replaced with alternatives (with some re-categorized to QPS) (MBTOC 2018, TEAP 2022).

Since 2005, the total amount of MB requested for critical use nominations (CUNs) has fallen from 18,700 t to 43.6 t for 2023/2024. By 2004, more than 120 critical uses had been requested for preplant soil use by 10 non-A5 Parties plus the European Union; whereas in 2022, MBTOC only received 3 nominations from Australia, Canada (strawberry runners) and South Africa (houses). This shows a clear trend towards successfully replacing MB for controlled uses globally (TEAP 2022, MBTOC 2022).

In addition, the increased interest in organic agriculture (OA) has driven research into non-synthetic alternatives to pest control. OA is practiced in 187 countries, on 72.3 million hectares representing 1.5 % of the total agricultural land. OA is managed by at least 3.1 million farmers (FAO 2021a, FIBL and IFOAM 2021). Consumer demand for organic products will continue to grow driven by food safety concerns and increasing affluence. OA is perceived by many as having fewer negative effects on the environment than conventional agriculture because applications of soluble mineral fertilizers, and synthetic are not allowed, however copper use in OA has some negative impacts on the human health and on the environment.

Since the 2018 Assessment Report, a large number of research and review articles on alternatives to MB have been published, providing Parties with information on their relative effectiveness for a wide range of productive sectors. Over the years, MBTOC has identified a range of key chemical alternatives that perform consistently across most regions and sectors Restrictions on the use of many chemical fumigants compelled the adoption of nonchemical strategies for example: resistant cultivars, grafting, substrates, steam, solarisation, biofumigation, organic amendments, anaerobic soil disinfestation (ASD) and biological control (TEAP 2022, Gullino *et al.* 2022). These treatnments are aimed at more focus on maintaining soil microbial diversity, thus enhancing soil and plant health.

There are numerous examples of key sectors around the world in both A5 and non-A5 countries which previously usied MB, which have successfully adopted alternatives over a wide range of cropping systems. In most areas where MB has been replaced it has been demonstrated that no single chemical or non-chemical alternative has fully replace MB as a soil fumigant. Often a combination of treatments within an IPM program has been used to yield the best results. Soil treatments may be limited in their efficacy in specific areas due to, for example the availability of active ingredients, climatic factors, cultural practices, regulatory constraints and economic issues (Gullino *et al.* 2022).

Soil fumigants are a class of pesticides used to control soilborne pests and are applied as a pre-plant soil treatment in amany generally high value horticultural crops. key characteristic of common fumigants is their ability to move freely in the atmosphere over great distances as gases. Despite mandated protective equipment, application methods, and access restrictions, exposure risks remain for agricultural workers and communities near fumigation sites. However, many conventional and widely used soil fumigants, such as chloropicrin and 1,3-dichloropropene, have been identified as toxic and/or possibly carcinogenic. Acute and chronic exposure risks may include irritation to the eyes, skin, and respiratory system, as well as nausea, vomiting, increased risk of certain cancers, and in extreme cases, death (Besri 2021, Gullino *et al.* 2022). For these reasons, there is concern that the future of many alternative fumigants to MB may not be sustainable and efforts need to continue to find alternative pest comtrol measures without chemical fumigants.

Some non-chemical alternatives using copper or plastic mulch for soil fumigations, have also a negative impact on humans and on its environment (INRA 2018, Eosta 2021, FAO 2021b). Therefore, human safety, in addition to environmental health should remain central when proposing effective alternatives to MB and exploring sustainable agriculture.

This chapter of the assessment report reviews the progress made in development and adoption ofchemical and non-chemical alternatives and discusses some aspects of their use on the user and on the environment.

6.3. Alternatives to methyl bromide for soil uses: State of the art

6.2.1. Non-chemical alternatives

The key non chemical alternatives taken up to replace MB have been the use of resistant varieties, or grafting solarization, biosolarization and biofumigation. The success has been dependent on the location, materials used, and target pests (MBTOC 2018, Porter and Fraser, 2020; Gullino *et al.* 2022)**.**

6.2.1.2. Biological alternatives as a component of IPM

a-Resistant cultivars

Commercial cultivars that are resistant to or tolerate one or more soilborne pathogens are available for many crops (Lefebvre *et al.,* 2020). Development of improved strawberry cultivars with resistance to root and crown rot diseases caused by *Phytophthora cactorum*, *Macrophomina phaseolina,* and *Colletotrichum* spp., as well as increased fruit quality, helped strawberry growers who were affected by the MB phase-out (Li *et al*., 2020). However, resistant genotypes are not always completely protective under field conditions that are highly favorable to disease development. Under severe infection of crops, new pathogen races can appear and infect the resistant cultivar.

b-Grafting

Grafting that uses resistant rootstocks is increasingly used to control soilborne diseases in vegetables, particularly tomatoes, cucurbits, peppers and eggplants in many countries. They are generally adopted as part of an integrated pest control system and have led to the reduction or complete replacement of methyl bromide use in different countries (Suansia and Samal, 2021). Recent studies focus on improving the tolerance of vegetables to abiotic stresses including soil salinity, drought, heavy metals, organic pollutants and low and high temperatures (Arwiyanto *et al.,* 2018, Bogoescu *et al.,* 2018, Koufakis and Kintzonidis, 2018, Besri 2008a, Besri 2008b). These disease resistant root stocks are available for some crops but unfortunately not for others (Quamruzzaman *et al.,* 2020, Maurya *et al,.* 2019, Rakha *et al.,* 2020).

c-Soil less culture

Soilless cultivation avoids the need for soil fumigation. This method is now widely used for high-value vegetable and ornamental crops such as rose, carnation, gerbera, basil, spinach, and lettuce but it is also expanding to other crops such as strawberry fruits and runners (Savvas and Gruda 2018, van Os, 2017).

In particular, flotation systems, based on soilless substrates and hydroponics, have replaced the majority of MB for tobacco seedling production worldwide (Carrasco *et al.,* 2003, Kanatas 2020).

d-Anaerobic soil disinfestation

Anaerobic soil disinfestation (ASD) is a biologically based, non-fumigant, pre-plant soil treatment developed to control a wide range of soilborne plant pathogens and nematodes in numerous crop production systems (Guo *et al.,* 2018, Muramoto *et al.,* 2018, Shennan *et al.,* 2018, Gilardi *et al.,* 2020). ASD uses a process of disinfesting soil by creating anaerobic soil conditions with the incorporation of easily decomposable soil amendments, covering with plastic mulch, and irrigating to saturation before planting.

e-Biofumigation

Biofumigation is the practice of using volatile chemicals released from decomposing plant biomass to control soil borne pests, including nematodes, bacteria and fungi. The use of Brassica cover crops and their associated degradation compounds as biofumigants to manage soilborne pathogens offer vegetable growers an alternative to MB (Besri 2021a, Besri 2021b, Back 2021).

A number of studies (Hoffmann *et al.,*2020; Ren *et al.,* 2018; Zhu *et al.*, 2020) reported that allyl isothiocyanate (AITC), a natural product obtained from *Brassica,* has high biological activity against major soilborne pathogens in cut flowers and strawberry and increased plant vigor, yield and farmers' income.

f--Biological control

Biological control using antagonistic microorganisms could be an environmentally friendly way to control soilborne pathogens in most crop production regions all over the world. The use of beneficial microorganisms such as diazotrophs, bacteria, biological control agents (BCAs), plant growth promoting rhizobacteria (PGPRs), in the replacement or the reduction of chemicals has been reported by many authors (Wright and Bennett 2018, Etesami and Maheshwari 2018, Bi *et al.,* 2018, Gangadhara *et al.,* 2022). However, some studies on biological control of soilborne pathogens in the last few decades have led to relatively few practical applications (Bardin and Pugliese, 2020). The chances of success with biological control may be greater for greenhouse crops because the environment can be controlled to a greater extent than in the field (Bardin and Pugliese, 2020).

g-Trap Crops

A trap crop is a plant that attracts agricultural pests (fungi, insects, nematodes) away from nearby crops. This cultural practice can save the main crop from decimation by pests without the use of pesticides. The trap crop such as Marigold (*Tagetes* spp.) is grown before the main cash crop is planted (Westerdahl 2018, Karakas and Bolukbasi 2019, Besri 2021a).

6.2.1.3. Physical alternatives

a-Steam

Steam disinfestation is an increasingly attractive strategy to control soilborne pathogens and weeds both in greenhouses and field crops. Soil disinfestation with steam has potential to partially replace fumigants such as methyl bromide, chloropicrin, and 1,3-dichloropropene. In California, soil disinfestation with steam has been tested successfully in strawberry daughter plants production (Steven *et al.,* 2016, Fennimore and Kim 2020, Fennimore *et al.* 2021, Kim *et al.*, 2022). Higher control was obtained when steam was combined with mustard seed meal (MSM) (Kim *et al.*, 2021) or with allyl-isothiocynate (AITC) (Kim *et al.* 2020). Using steam plus MSM as pre-plant disinfestation treatments in organic production showed higher yields than steam alone (Michude *et al.*, 2021).

b-Solarisation and biosolarisation

Since its development, soil solarization has been applied in more than 70 countries. The advantages of soil solarization are its simplicity, ease of application, and lower cost compared with most other soil-disinfestation technologies (Gamliel and Katan 2012, Besri *et al.,* 2012). Limitations of this method are its climate dependence and the fact that, during its application, which lasts 3 to 6 weeks, the soil is without crops. Additionally, it does not consistently control certain pathogens, such as nematodes (Chellemi *et al.,* 2016).

c-Hot water and heat treatment

Hot water treatment is used in Japan to control soilborne pathogens in protected houses for ornamental and vegetable crops particularly in repeated cropping systems (Fujinaga *et al.,* 2005, Gyoutoku *et al*., 2007, He 2018).

d-Microwaves

Microwave soil treatment has some important advantages over other thermal soil sanitation techniques, such as steam treatment because microwave soil sanitation does not sterilize the soil, but favors beneficial species of soil biota making more nutrients available for better plant growth. (Vintila *et al.*, 2018, Khan *et al*., 2019, Brodie *et al.,* 2019, Brodie *et al.*, 2020, Graham *et al.*,2020). Brodie *et al.* (2022) showed that microwave treatment in two strawberry runner field experiments reduced the survival of buried soil borne pathogens and gave equivalent yield to soil fumigated with MB:Pic.

e- Soil flame disinfestation

Soil flame disinfestation (SFD) is a non-chemical, safe, and environmentally friendly method. It is used both in greenhouses and in open fields to control soil borne pathogens and weeds. (Wang *et al.,* 2020).

6.2.2. Chemical alternatives

6.2.2.1. Fumigant pesticides

Since the 2018 MBTOC Assessment Report (MBTOC 2018), important changes in the registration and commercial adoption of chemical alternatives to MB have taken place. For example, in all EU member states, fumigants once regarded as MB alternatives (chloropicrin, 1,3-D, MITC generators) are restricted in use (EU 2016). In addition, registration for methyl iodide (MI) once believed to be an effective replacement for MB has been withdrawn by the manufacturer almost worldwide, although a recent registration is being considered for treatment of soil for strawberry runners in Australia (CUE application 2022). Alternative fumigants that are currently available and widely used are briefly described in the following paragraphs.

- Chloropicrin (Pic) is effective for the control of soilborne fungi and some insects but has limited activity against weeds (Ajwa *et al.,* 2003). Combination with virtually or totally impermeable films (VIF, TIF) has been an effective strategy to reduce application rates keeping satisfactory efficacy (Chow 2009).
- 1,3-Dichloropropene (1,3-D) is used as a nematicide and provides effective control of insects and suppresses some weeds and pathogenic fungi (Gullino *et al.* 2022). As with Pic, 1,3-D can achieve similar efficacy when combined with virtually or totally impermeable films (VIF, TIF) at reduced dosages (Chow 2009). In 2022, 1,3-D and Pic have not been approved by the European commission **(**Commission implementing regulation (EU) 2022/74 of 13 May 2022 and EU 2022/751) as of 16 May 2022.
- Fumigants based on the generation of methyl isothiocyanate (MITC), including dazomet, metam sodium and metam potassium, are highly effective at controlling a wide range of arthropods, soilborne fungi, nematodes and weeds, but are less effective against bacteria and root-knot nematodes. Their efficacy increases when they are combined with Pic or 1,3-D (Culpepper 2008, Stevens and Freeman 2018).

- Iodomethane or methyl iodide (MI) is a liquid fumigant which has been tested on a wide range of crops by drip and shank-injected and found to be highly effective at controlling a wide range of soilborne pathogenic fungi, nematodes, and weeds (Schneider *et al.,* 2008, Schneider *et al.,* 2009).
- DMDS has been registered for preplant soil fumigation in many countries. It is applied by shank injection or drip application and has proven effective for controlling a broad spectrum of soilborne weeds, pathogens, and nematodes. In the United States, DMDS is commonly mixed with chloropicrin prior to application and this combination is very effective (Heller *et al.* 2009, Heller *et al.,* 2010, López-Aranda *et al,* .2009a, López-Aranda *et al,*. 2009b, Ajwa and Mona 2013). DMDS efficacy can be enhanced when combined with VIF or TIF films (Chow 2009).
- The pre-plant soil fumigant ethane dinitrile (EDN) has shown promising activity against several key soilborne pathogens including plant-parasitic nematodes, and weeds (Stevens and Freeman 2018, Stevens *et al.,* 2019, Stevens *et al.,* 2020). With chemical properties similar to those of methyl bromide, EDN has the potential to move readily through the soil profile. In 2018, Australia became the first country to approve the use of EDN for production of strawberry runners, strawberries, fruits, cucurbits, and ornamentals. EDN has also been registered in Korea and it will be registered in other countries (Turkey, South Africa, Canada, the United States of America., Russia, New Zealand and Malaysia; Stevens *et al.,* 2020).
- Ethylicin has been reported as a soil fumigant against some plant pathogens and nematodes (Li *et al.,* 2022).

Currently, most single chemical alternatives target specific groups of organisms and therefore combinations of fumigant chemicals are generally used to give broad scale treatment comparable to MB. With the exception of methyl iodide, it is clear that none of the currently available fumigants, used alone, offer a completely satisfactory alternative compared to MB (Di Primo *et al.,* 2003; Triky-Dotan *et al.,* 2009). Obviously, the future of soil disinfestation lies in combining available fumigants with other chemical and non-chemical alternatives.

6.2.2.2. Non fumigant pesticides

Recently, some new non-fumigant nematicides (NFNs), such as fluensulfone (Nimitz) and fluopyram (Velum) have become available and have shown good promise to manage nematodes. Current research has been conducted to know if NFNs can be used as stand-alone products or as a component of an integrated management strategy for nematode management (Desaeger *et al.,* 2020; Giannakou and Panopoulou, 2019; Kawanobe *et al.,* 2019; Meza *et al.,* 2021).

6.2.2.3. Natural pesticides

With the increasing awareness of the necessity for the protection of the environment and human health, highly toxic chemicals no longer meet the developmental requirements of modern agriculture. Recently, many studies have been undertaken on the isolation and activity of natural products against plant-parasitic nematodes (Chen and Song, 2021).

6.2.3. New practices and technologies

Modern agriculture is shifting towards sustainable practices and technologies for food production. New practices and technologies have recently been developed as alternatives to MB.

6.2.3.1. Innovative technologies with plastic mulch films

Plastic mulches, coated with different pesticides (herbicides, fungicides and nematicides), have been developed to control many pathogens, weeds, and nematodes. The coated mulch can be effective in soil disinfestation like soil fumigants but with significant lower application rates, fewer application steps and without emissions or drift (Dujardin, 2020).

Xuan *et al.* (2011) developed a reactive later, containing dry ammonium thiosulfate, that was set between a lower layer of HDBE and an upper layer of VIF, that would bind with MB and therefore could reduce MB loss from fumigated soils to the atmosphere. Further studies on reactive films were conducted to mitigate other soil fumigants such as 1,3-D, chloropicrin, and methyl iodide (Xuan *et al.* 2012)

6.2.3.2. New formulations of fumigants

Soil fumigants have been extensively applied for decades in growing high-quality food crops around the world. However, thechemical fumigants generally create volatile organic compounds (VOCs) with high volatility, corrosivity, and toxicity. Commercial formulations of fumigants such as chloropicrin and dimethyl disulfide rely on the liquid forms applied by shank injection or drip irrigation (Kim *et al.* 2003). However, direct use of the liquids requires high dosages, causing substantial air and ground water pollution, due to the high volatility and mobility of the liquid chemicals, as well as significant safety hazards to workers during handling and transporting. Therefore, developing appropriate formulations of fumigants and minimizing their potential risk on the environment and non-target species is highly desirable in both agricultural and environmental chemistry. Recent advances have been made in formulations include encapsulating fumigants in gelatin capsules (Yan *et al*., 2012, Wang *et al.,* 2020) and using polyurea microcapsules for controlled release of solid modified biochar and liquid allyl isothiocyanate (Ren *et al.* 2022), dazomet (Ren *et al.,* 2022), and dimethyl disulfide (Ren *et al.,* 2021). These new formulations have been shown to be more effective in controlling soilborne pathogens and weeds with no phytotoxicity.

6.2.3.3. Site specific fumigant management

Site-specific fumigant soil management facilitates adjustment of fumigant rate within a field based on actual pathogen load and distribution rather than the current single rate fumigation. Variable rate fumigant application reduces total fumigant applied by allowing for a higher rate of application in areas with high pathogen pressure and less fumigant in areas with low pathogen pressure. Precision fumigation will reduce net amount of fumigant applied while disease management will be equal or better than traditional single dose fumigation strategies (Martin *et al,,* 2020).

6.2.3.4. Disinfestation with steam in California strawberry nurseries.

Soil disinfestation with steam has been tested successfully in strawberry fruiting fields, but little is known about use of steam for field production of strawberry daughter plants. Daughter plant production was compared in soils treated with steam vs. the methyl bromide and chloropicrin (MB:Pic) standards. The results indicated that the pest control and daughter plant production were similar in steam and MB:Pic treated soils. Therefore, soil disinfestation with steam may be a viable method to use in strawberry nurseries although more research is needed to verify plant sanitation and quality. There is also a strong interest from plant industry to produce strawberry plants for the organic market without using fumigants (Fennimore and Kim, 2020).

6.2.3.5. Chlorine dioxide (ClO_2) granules as alternative to MB

Layman *et al.*(2020) and Ramsey and Mathiason (2020) reported that chlorine dioxide (ClO_2) granules is a promising alternative to soil fumigation with methyl bromide to control *Phytophthora ramorum* and *Bacillus subtilis*. However, further research is needed to refine the granule formulation release rates and develop more economical application rates.

6.2.4. Integrated Pest Management

Soil disinfestation has evolved during the last 60 years from using a single measure (steaming or fumigation) to integrated management. Soil disinfestation is the major pillar of any IPM approach for managing soilborne pests and achieving soil health. The problems generated in many agricultural regions and systems by the phaseout of MB made it clear that dependence on a single method should be avoided and that traditional but still effective methods such as crop rotation, use of organic amendments, and grafting should be reintroduced (Gabarra and Besri 1999, Katan *et al.,* 2012, Katan and Vanachter, 2010; Gullino *et al.,* 2022).

The Integrated Pest Management (IPM) method combines various techniques (biological, cultural and physical) to minimize the extent of environmental degradation and reduce the impact of chemical inputs on humans and non-target organisms. IPM is a critical component of the sustainability of many agro-ecological systems. Pesticides are used only if they are needed, and treatments are made with the goal of removing only the target organism. Pest control materials are selected and applied in a manner that minimizes risks to human health, beneficial and non-target organisms, and the environment."

- Biofumigation, grafting and soil solarisation: Brassica green manure and Brassica defatted seed meal were successfully applied in combination with grafting and soil solarization against Verticillium wilt of eggplant and Fusarium wilt of lettuce and basil (Garibaldi *et al.,* 2011).
- Resistant varieties and fumigation: The integration of soil disinfestation with resistant plant genotypes offers a wider and improved disease suppression, resulting in enhanced crop production. Soil fumigation enhanced nematode suppression and increased tomato fruit yield in a nematode-resistant cultivar grown in infested soil (Regmi and Desaeger 2020).
- Grafting and fumigation: For crops such as tomato and bell pepper, the combination of grafting on resistant rootstock and soil fumigation with dimethyl disulfide or metam sodium was effective (Garibaldi *et al.* 2008; Gilardi *et al*., 2013; Zaaroor *et al.,* 2016).
- Grafting and solarisation; The added value of combined solarization and grafting was demonstrated with eggplant (Ioannou 2001), watermelon (Zaaroor *et al*., 2016) grown in nematode-infested soil.
- Solarisation and biocontrol agents: Solarization in combination with the biocontrol agents *Trichoderma harzianum, Gliocladium virens* or *Streptomyces griseoviridis* was effective against various soil borne pathogens (Chet *et al.,* 1982, Minuto *et al.,* 2006).
- Solarisation and reduced rate of fumigants; Solarisation is now increasingly combined with low doses of fumigants, as part of IPM programs to replace MB for controlling soilborne pathogens and weeds in many crops including vegetables and ornamentals with excellent results (Katan and Gamliel 2010, 2012; Gamliel, 2018; Gamliel *et al*., 2018). Combining fumigants with solarization is now well accepted and commonly practiced. An improvement in this technique was reported by Eshel *et al*. (2000), who showed that sequential application of solarization first, then fumigant injection 2 weeks later, further enhanced pest control at a reduced fumigant rate. This approach is now widely adopted in Israel in fields with drip-irrigation system or with side-shank injection using a special machine (Gamliel 2012).
- Soil less culture and other alternatives: Soil less culture can be used in combination with other options, for example compost, grafted plants and/or biocontrol agents, providing very good results (Thomas *et al*., 2011; Fennimore *et al*., 2013; Evenhuis *et al.,* 2014; Colla *et al*., 2012; Marsic and Jakse 2010).

6.3. Alternatives for the remaining MB critical uses in the soil sector

Since 2003, quantities of MB requested for critical use have fallen from 18,700 t for use in 2005 to 150 t for 2019/2020. In 2018, 2019, 2020and 2021 MBTOC received 4 critical use nominations for soil fumigation from 3 Parties (Argentina, Australia and Canada) and 3 in 2022. Technically and economically feasible chemical and non-chemical alternatives to MB have been found for virtually all soils applications for which MB was used in the past, and comprehensive information is available for these uses.

Technically and economically feasible chemical and non-chemical alternatives to MB have been found for virtually all soils applications for which MB was used in the past including nearly all critical uses applied for since 2005.Comprehensive information is available on the adoption of key alternatives (MBTOC, 2018; TEAP 2022).The TEAP May 2022 progress report provides updated information on recent research related to alternatives for soil-controlled uses of MB for which critical uses are still being requested, namely strawberry runners (soilborne pathogens and weeds) (TEAP 2022).

6.3.1. Strawberry runner production: Australia

Australia continues to prioritize the registration of Methyl Iodide (MI) as the most efficient alternative to MB for treating soil grown with strawberry nurseries in the State of Victoria. Extensive R&D in the runner industry at Toolangi, Victoria, proved that soil disinfestation with MI/Pic controls soilborne pathogens and weeds as effectively as MB/Pic, and produces equivalent runner yields to MB/Pic in commercial trials. Although in 2012 Arysta Life Sciences withdrew its application to register MI in Australia and other countries around the world, Saluterra Pty Ltd has applied for registration of MI/PIC 980 soil fumigation strawberry runner production. The product has been shown to control *Fusarium, Pythium, Phytophthora, Rhizoctonia, Sclerotium rolfsii, Macrophomina phaseolina*, other plant parasitic nematodes and some weed (TEAP, 2022).

The Australian research program continues to look at other alternatives with encouraging results: ethane dinitrile (EDN), TF-80®, microwave treatments, and different rates and formulations of MI/Pic. DMDS and DMDS/Pic are trialed in Australia since 2014 and Arkema is proceeding with registration (TEAP, 2022).

6.3.2. Strawberry runner production: Canada

Many countries producing strawberry runners find soilless culture systems technically and economically feasible, at least for a portion of certified nursery production operations, as well as for stock plants. Such systems allow for producing pest and disease-free nursery material that meets the required plant health standards (López-Galarza *et al*., 2010; Rodríguez-Delfín, 2012; Xu, 2019; Wei *et. al*., 2020).

Canada continues to conduct research aimed at perfecting a soilless production system that will avert the need for soil fumigants, as no chemical alternatives to MB are allowed on Prince Edward Island, where the need for a CUE arises. Other Canadian Maritim provinces do not need MB to produce healthy strawberry runners in similar circumstances.

6.4. Strawberry fruit production: Argentina

Allyl isothiocyanate (AITC) is a biofumigant that has been registered in the United States to control fungal soilborne pathogens such as *M. phaseolina* (charcoal rot). Investigating AITC under Argentinean conditions for management of this strawberry disease has been demonstrated (Baggio *et. al*. 2018). In Florida, dimethyl disulfide (DMDS) combined with metam potassium- or chloropicrin-controlled tomato soilborne pathogens and weed (Boyd *et al.,* 2017; Yu *et. al.,* 2019). In Argentina, Del Huerto (2013) found no difference between MB and 1,3-D/Pic, which makes the latter a good alternative option. Jaldo *et al*. (2007) showed that 1,3-D/Pic injected in the soil gave better yields than methyl bromide in Lules/Tucumán.

Aldercreutz and Szczesny (2008, 2010), showed that yields obtained in Mar del Plata with metam sodium and metam ammonium were comparable to those produced with MB. Bórquez and Agüero (2007) found that weed control achieved with metam ammonium, metam sodium and metam potassium in Lules, was comparable to that obtained with MB 70:30, and that yields obtained with these treatments there were not significantly different. Other studies have confirmed these results (Bórquez and Mollinedo 2009, Bórquez and Mollinedo 2010, Aldercreutz and Szczesny, 2008; Bórquez and Agüero, 2007).

Since 2017, substantial progress has been made in testing and commercially implementing soil-less culture in strawberry fruit production. This technique expanded in 2018 and 2019 in new projects in Santa Fe, Buenos Aires and Tucuman provinces of Argentina, using inert substrates, under macro tunnels where plants are fertigated via a drip system (INTA, 2018; La Capital Mar del Plata, 2019; La Gaceta de Tucumán, 2019).

6.5. Greenhouse tomatoes production:Argentina

6.5.1. Non-chemical alternatives

Rotating tomatoes with other non-susceptible crops has proven important for its control (EFSA 2018, Vasquez-Sanchez *et al.,* 2018). Despite the high number of compatible and efficient rootstocks available for tomato production, there is no indication of any that might be resistant to *N. aberrans.* It has been demonstrated that *Mi* genes are not effective against *N. aberrans* and no reliable sources of resistance against this nematode in tomato have been found (Gutiérrez *et al.,* 2014; Andreau *et al.,* 2014).

At INTA San Pedro, many biosolarisation experiments have been conducted since 2003. Organic amendments tested in these experiments include chicken manure, broccoli, tomato and pepper crop debris, brassicas such as rapeseed, broccoli, mustard and other materials (Mitidieri *et al*., 2015; 2017a, 2017b; Pagliaricci *et al*., 2015; Lafi *et al.,* 2017)**.** The fungal pathogens controlled in these experiments were *Pyrenchaeta lycopersici*, *Fusarium solani*, *Sclerotium rolfsii* and *Sclerotinia sclerotiorum*, as well as nematodes like *Nacobbus aberrans*, *Helycotylenchus* spp. and *Criconemella* spp. In La Plata, biosolarisation using broccoli as organic matter has been evaluated with good results to control tomato soilborne pathogens, including *N. aberrans* (Martinez *et al*., 2013).

Further interest in soilless culture (substrate cultivation and hydroponic systems) is increasing. Different organic and non-organic materials, often combined, have been tested. Commercial substrates and soluble fertilizers for use with irrigation systems are available (Osvaldo, 2016; 2017; Osvaldo and Czepulis, 2017).

Finally, biocontrol agents including *Paecilomyces lilacinus, Arthrobotrys conoides* and *Pochonia chlamydosporia* have been found to reduce *N. aberrans* populations (Franco-Navarro *et al.,* 2016; Sosa *et al.,* 2018; Caccia *et al.,* 2018; Gortari and Hours, 2019; Cortez Hernandez *et al.,* 2019).

6.5.2. Chemical alternatives

Chemical alternatives are available for controlling *N. aberrans*. For example, Fluensulfone (Nimitz®) is a contact nematicide with low human and environmental impact that targets nematodes including *Nacobbus* (Hidalgo *et al*., 2015). Giannakou and Panopoulou (2019) reported significant reductions in population density, reproduction rate, and root galling of N. aberrans with fluensulfone applications on tomato and cucumber. In other studies, mixtures of 1,3-D/Pic (for example 40:60) and fluensulfone showed lower galling index compared to the fumigant alone (Castillo *et al*., 2016).

Successful research on combined chemical and non-chemical (biofumigation, solarisation, grafting, and biological control) alternatives has been conducted, yielding promising results for controlling *Nacobbus* (Quiroga *et al.,* 2014; Franco-Navarro *et al*., 2016; EFSA, 2018; Garbi *et al*., 2018a; Garbi *et al*., 2018b; Garita *et al.* 2019).

6.6. Remaining and emerging challenges impacting MB phase-out for soils use

The CUNs presented in 2019, 2020, 2021 and 2022 by two non-A5 countries for strawberry runner production (Canada and Australia) and one Article 5 country for tomato and strawberry fruit production cited several categories of reasons for CUNs (MBTOC, 2019; MBTOC, 2020; MBTOC, 2021; MBTOC, 2022):

- Absence of identified alternatives: for example: resistant cultivars and rootstocks to a broad spectrum of pathogens;
- Lack of chemical registration by regulatory authorities;
- The cost and length of time required for obtaining r,egistration;
- Insufficient time to develop the necessary infrastructure: for example: commercial nurseries;
- Lack of training in the use of alternative and adaptation of the process to local conditions: for example: soil less culture and biofumigation;

- Unsuitability of available alternatives for local conditions: for example: solarization;
- Longer time between fumigation and planting (plant back periods) with the use of some alternatives, causing disruption to cropping programs: for example: metam sodium, dazomet, and chloropicrin;
- Available and suitable alternatives are not economically viable: for example: propagative materials, steaming, soilless cultivation, and electric energy availability at farm level.

The availability of alternatives, including those already adopted and those under development, could change in the medium to long term due to a number of issues including regulatory restrictions from environmental and health issues, increases in energy usage and application costs.

6.7. Impacts of some chemical and non-chemical alternatives to methyl bromide adopted in the soil sector, on the Sustainable Development Goals (SDGs)

6.7.1. Methyl bromide emissions

Open field burning practices once used in the US Northwest (Idaho) to prepare fields for subsequent planting was closely monitored and controlled by the state department of agriculture (McCarty *et al.* 2009). In potato fields, treated with methyl bromide to control the golden cyst nematode, about half of the bromine and chlorine up taken from the subsequently planted alfalfa was retained in the residue of ash/unburned alfalfa while the remainder was likely emitted. The MB levels in the smoke from treated alfalfa were two orders of magnitude higher than levels in smoke from untreated alfalfa (Aurell *et al.* 2022).

6.7.2. Copper use in organic agriculture

Organic products have become increasingly popular in recent years, as consumers have grown more health conscious and environmentally aware. Many stores and supermarkets now have large sections devoted to organic fruits and vegetables. Organic agriculture (OA) is an agricultural system which is considered as alternative of MB.

As OA prohibits the use of synthetic pesticides, including MB, it relies heavily on the use of copper to control a variety of fungal and bacterial diseases as it is approved for use in OA. However, demonstrated negative effects of copper on human health and the environment have been reported. For example, Coelho *et al.* (2020) showed a correlation between copper use in agriculture and Alzheimer incidence. Copper has also a negative impact on the environment notably on soil organisms and crop auxiliary species. This has led to regulatory restrictions on the copper use /prohibition in several European countries (European commission, 2011; Karimi *et al.,* 2021; Kuhne, 2017; Katsoulas, 2020). In the U.S., copper use is allowed for OA, but has restrictions (USDA, 2022).

Alternatives to copper have been identified, developed, and commercialized: disease-resistant varieties; natural substances with biocidal effects and/or the capacity to stimulate natural plant defenses; antagonistic microbiological agents; management of crop canopies to prevent disease, and IPM (Kühne *et al.,* 2017; Eosta, 2021; INRA, 2018).

6.7.3. Plastic mulching films

Most mulching films (for example VIF, LDPE) used in soil disinfestation (for example chemical fumigants, bio fumigants, solarisation) are single use and can persist in the environment long after their intended use (Besri, 2021; FAO, 2021b; Wijesekara *et al.,* 2018). Degrading into microplastics, they can transfer and accumulate in food chains, threatening food security, food safety and potentially human health. Their widespread and long-term use, coupled with lack of systematic collection and sustainable management, leads to their accumulation in soils and aquatic environments. Soils are one of the main receptors of agricultural plastics and are known to contain larger quantities of microplastics than oceans. Only small fractions of agricultural plastics are collected and recycled, predominately in developed economies. Elsewhere, most plastics are burned, buried, or land filled. Promoting circular approaches is essential to reduce plastic waste generation through prevention, reduction, reuse and recycling (Besri, 2021; FAO, 2021b).

6.7.4. Release of dinitrous oxide (N2O) in the atmosphere by ASD

It has been reported that agricultural soil is an important source of dinitrous oxide (N_2O) in the atmosphere (OECD, 2021). Chemical soil fumigation with chloropicrin has reported increases in N_2O production up to 25 times relative to water control (Fang *et al*., 2018). The soil fumigation alternative known as anaerobic soil disinfestation (ASD), which is considered a possible replacement for chemical soil fumigation (Shrestha *et al.,* 2016), has also been reported to generate similar levels of N_2O when using composted poultry levels (Di Gioia *et al,.* 2017). A longer-term study comparing eight different treatments that included ASD and chemical soil fumigation, showed no differences in cumulative N_2O emissions throughout a complete tomato cropping cycle (Li *et al*., 2022).

6.7.5. Energy consumption by microwaves

Microwaving soil has the benefit potential to reduce populations of important soilborne pathogens, including *Pythium*, *Fusarium*, and most nematode species (Ferriss, 1984) while maintaining some beneficial microbes such as nitrifying bacteria and archae (Brodie *et al.,* 2021). For field applications, an extremely high-power level would be required to generate the necessary microwave energy application for soil pest control and so safety for the operating personnel must be considered (Nelson, 1996). A proper shield design would be needed to ensure that energy radiated to surroundings is maintained below safe levels for human exposure.

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7

7. Alternatives to Methyl Bromide for Structures and Commodities

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7.1 Introduction

Methyl bromide (MB) was mentioned as a treatment for postharvest pest control for the first time by Mr. Le Goupil in 1932. It rapidly became established as a fumigant of choice for whole site fumigation of grain mills and of bag stacks of grain, particularly in USA and the continent of Africa.

MB was recognized as an Ozone Depleting Substance under the Copenhagen Amendment in 1992. Over the next three decades alternatives for almost all previous controlled uses of methyl bromide have been identified, developed and put into practice, replacing its use for pest control in structures and commodities (SC). European countries were able to completely phase out MB in use for the disinfestation of structures and commodities (SC) in 2005 with only a few requests for Critical Use Exemptions (CUE); the last nomination from this region was made for 2008 use, followed by a complete ban for all uses and production, including for quarantine and preshipment (QPS) in 2010.

MBTOC has reported extensively on MB alternatives for SC in its past Assessment Reports (2011, 2015, 2019) and these reports provide thorough information on the subject. This chapter thus focuses on the last critical uses remaining since 2018, whilst providing an overview of alternatives adopted for the different previous uses.

This 2022 MBTOC Assessment Report provides an overview on the information and progress of replacement of methyl bromide used for various fields of pest control around the world. It comprises information on research on pest control in structures and commodities, especially during the past four years, including updating of alternatives for the remaining controlled uses of MB for which critical use exemption was and is still requested during the past four years, namely for the disinfestation of flour mills until 2022, and the control of insect wood pests in wooden parts in roofs of houses.

7.2 Alternatives for Structures and Durable Commodities (Controlled, non-QPS)

Researchers around the world continue to conduct research aiming at identifying and adopting alternatives to MB for controlling pests causing problems in the structures and commodities sectors (Ducom, 2012). However, as of 2015, all postharvest uses of MB have been phased out in non-A5 Parties and no CUNs have been submitted since. The increase of resistance of many pest species towards insecticides, the reduction in the number of active registered compounds and, the adverse impacts on the environment are also relevant reasons to develop alternatives to the use of toxic compounds for stored products pest control (Phillips and Throne, 2010; Riudavets, 2018).

Technically and economically feasible chemical and non-chemical alternatives to MB have been found for the disinfestation of virtually all infested structures and durable commodities for which MB was used in the past including nearly all critical uses applied for since 2005. Comprehensive information is available on the adoption of key alternatives are described in the MBTOC 2018 Assessment Report (MBTOC, 2019), past MBTOC CUN reports (MBTOC, 2003 - 2020) and the MBTOC progress reports

(TEAP, 2003-2022). Additionally, there are good overviews of alternartives for specific uses such as in Australia the Grains Research and Development Corporation GRDC has published in 2020 a handbook on grain storage, including various aspects of logistic, economy and pest management (GRDC, 2020).

7.2.1 Chemical Alternatives for SC Uses and Possible Options for MB-Use

During the initial MB phase-out years, the main alternatives used for its replacement were other available and registered fumigants. In ensuing years, registration of new and rediscovered fumigants occurred for use on dry (durable) foodstuffs (Ryan *et al*. 2006). The phase in of controlled atmosphere treatments using gas mixtures with low oxygen content with carbon dioxide and/or nitrogen has been used against stored product pest insects (Navarro, 1978; Calderon and Navarro, 1980; Navarro and Calderon, 1980; Calderon and Barkai-Golan, 1990) and occurs also for disinfestations in museums (Review of Berzolla *et al*. (2011), often in gastight chambers. In some situations, intensive use of contact insecticides like pirimiphos-methyl, dichlorvos, pyrethroids (e.g., deltamethrin, permethrin, cyfluthrin), allyl-mercaptan (Chang *et al.* (2017), thiamethoxam and alpha-cypermethrin (Doğanay *et al*, 2018), and natural pyrethrines (Arthur *et al*., 2014; Campbell *et al*., 2017) occurred. Other insecticidal or at least repellent extracts of plants were also considered (and still are) as elements for potential replacements for MB and are subject to continuing research.

Pest control operators report success using phosphin**e** alone (Rogers *et al*., 2014; Ryan and Nicholson, 2014; Tütüncü *et al*., 2014) or a combination of heat, phosphine (at lower contents of several hundred ppm in air) and carbon dioxide, but note these measures need to be in place to protect susceptible equipment from corrosion by phosphine. Phosphine, released as a pure gas from cylinders, seems to be less corrosive. Carmi *et al*. (1994) and Reichmuth (1998) used carbon dioxide - introduced synchronically from the space on top of grain silos - to speed up the even distribution of phosphine - released from solid generators in the free space on top of the grain silo - throughout the grain bulk in silos. In Australia, Winks (1993) developed the phosphine fumigation further by continuously purging a low concentration phosphine/air mixture using a phosphine containing steel cylinder (see also Ryan and Nicholson, 2014).

Although phosphine has remained the fumigant of choice to replace MB in many postharvest treatments, some problems with its use need attention. In particular the potential development of resistant pests exist (Opit *et al.,* 2012; Nayak *et al*., 2020), especially, if the recommended boundary conditions for an effective fumigation i.e.combination of temperature, high gas tightness and appropriate dosage and length of treatment are not correct (Wohlgemuth, 1990; Reichmuth, 1993; Binker *et al*., 2004) Cato *et al*., 2017; Gautam *et al*., 2017; Jagadeesan *et al*., 2012; Jagadeesan *et al*., 2014; Collins *et al*., 2017; Konemann *et al*., 2017; Rafter *et al*., 2017; Sağlam *et al*., 2015; Venkidusamy *et al*., 2018).

Lampiri *et al*. (2021) have once again addressed the difficulties of obtaining full control with phosphine because of the lethal nature of this gas towards insects is not linear and dependent on concentration and/or exposure time. Winks (1971; 1984; 1985; 1987; 1993) has also described the same effect decades ago. Reichmuth (1991a) developed for the first time a phosphine resistance test that relied on the narcotic behaviour of susceptible and resistant adults and larvae of various species of stored product pest insects at concentrations of phosphine in air of 1 to 2 mg/l. The time for narcosis was much longer in resistant strains than in susceptible strains. After about 15 minutes all the susceptible insects were narcotised (not necessarily killed). Resistant insects were still active in the gas for many more minutes to hours. Cato (2015) wrote a thesis on this subject on *Tribolium castaneum* in the US and presented a good literature survey on this topic. Later, this finding led to the development of a professional test kit (for instance by DETIA-DEGESCH) for quick detection of resistant insects prior to beginning a fumigation just by using some living adults from the infested location for short phosphine exposure.

Nevertheless, phosphine fumigation has been established as the leading treatment of infested durable commodities. In Japan, Soma *et al*. (2018) developed aluminium phosphide generators for treating infested grain in silo bins. The generators were exposed to the free air space above the grain and recirculating air accelerated the even distribution of the gas. The decomposed generators could be removed from the bins without residue build-up in the grain. This technique was then adopted in Germany, USA and Australia. Cook (1980) patented the recirculation of phosphine in grain silos to speed up the disinfestation.

Reichmuth (1983) used Detia Bag Blankets - exposed into the airspace of grain silos - to treat the grain with phosphine by recirculating the gas/air mixture. The blankets were removed after treatment without residue build-up on the grain (Reichmuth 1991b, 1994). Agrafioti *et al.* (2020) used an automated video tracking software to distinguish susceptible and resistant stored product insects. Arora and Srivastava (2021) determined the temporal dynamics of phosphine fumigation against insect pests in wheat storage. Lampiri and Athanassiou (2021) and Gourgouta *et al.* (2021). reported on the insecticidal effect of phosphine towards the khapra beetle.

Sulfuryl fluoride (SF) became a prominent in-kind MB alternative in some regions following its registration in various countries, particularly for disinfestation of empty structures like flour mills, churches and other historic and cultural buildings (Williams and Sprenkel, 1990; Ducom *et al*., 2003; Binker *et al*., 2011; Buckley and Thoms, 2012) and some selected stored products (nuts (Cottrell *et al*., 2020) and dried fruit) the main in-kind alternatives to the disinfestation of flourmills and food processing premises are sulfuryl fluoride (SF, including combinations of SF and heat or phosphine) (Opit *et al*., 2016) and heat as full site treatment (volume of less than about 40,000 m^3 due to logistic limitations) or spot heat treatments. Myers *et al.* (2021) combined SF with propylene oxide to control the khapra beetle *Trogoderma granarium*. Treatment of commodities with SF has also expanded in the USA. SF is in use for disinfestations of museums (structures) against insect pests in Japan. SF is now extensively used for disinfestation of bulk grain in parts of Australia, where resistance to phosphine in some insect pests makes phosphine use ineffective (Jagadeesan and Nayak, 2017; Xinyi *et al*., 2017). Yildirim *et al*. (2012) used SF for treatment of the infested Istanbul-Beylerbeyi Palace.

Hydrogen cyanide (HCN) is also available for full site fumigation in some countries (Draslovska Services Group, pers comm., 2022). Stejskal *et al*., 2016; 2017 have also described the fumigation of empty structures against insect pests with HCN. Flour mill fumigation was carried out by Aulicky *et al*. (2015) and described by Hnatek *et al*. (2018). The risk of corrosion and length of aeration time after the treatment to get rid of all residual gas from the treated premise have to be taken into account. Draslovska Services Group is seeking to register **ethane dinitrile** (EDN) in various countries for different purposes of pest control (Steskal *et al*., 2018; Hnatek *et al*., 2018). For the actual registration status of EDN see chapter QPS for preplant soil treatment and timber and logs (Matt Hall, personal communication, 2022). In his communication, Matt Hall also provided actual information on the use of HCN (Bluefume^{TM}):

Major envisaged uses of HCN (Bluefume)

- Structural fumigation for empty structures i.e., mills, warehouses, food factories, poultry farms
- Fresh produce phytosanitary post-harvest treatment for selected commodities, i.e., bananas, pineapples, citrus
- Aircraft and ship-hold fumigation
- Potential grain & pulses treatment for the control of stored product pests
- Phytosanitary treatment for control of brown marmorated stinkbug (BMSB), cut flowers, and dormant nursery stock (bulbs, etc.)
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TABLE 7-1: REGISTRATION AND USES OF HCN AROUND THE WORLD

Active and [requested] registration in Country / Region	**Registered Use**
European Union, Singapore	Structural Fumigation
Malaysia	Structural Fumigation & Post-Harvest Treatment
New Zealand*, ACVM register (2020).	Structural Fumigation & Post-Harvest Treatment
Morocco	Aircraft & Structural Fumigation
Mauritius	Aircraft
[Australia, USA, India, Pakistan, Canada South Africa]	Structural Fumigation

Ethyl formate (EF) was (re-) considered as alternative chemical for SC disinfestation (Bansal *et al*., 2015; Kim *et al*., 2015; Hamdi *et al*., 2015; Ling *et al*., 2016; Abdelgaleil *et al*., 2016). Draslovka received registrations for ethyl formate (eFUME^{TM}) for treatment of post-harvest goods including pulses and grain in the following countries (Matt Hall, personal communication, 2022): Malaysia, New Zealand, Australia, Tunisia, Philippines, South Korea and South Africa. Pending is: USA, India and Saudi Arabia. Warshamana *et al.* (2016) controlled pests of stored rice and maize with VAPORMATE^{TM}, a mixture of ethyl formate and about 80% carbon dioxide.

Research on the use of **propylene oxide** (PPO) **and carbon dioxide** (Gautam *et al*., 2014), PPO with carbon dioxide and SF (Jimenez *et al*., 2014) and **PPO with ethyl formate** (Wolmarans *et al.*, 2017) as alternatives to methyl bromide continues, and these chemicals are being adopted in several countries.

The next step for these promising research programs is to evaluate the likely economic performance and if positive the company may seek registration and plan for enhanced market penetration. These processes are very time consuming. Often, the market for new fumigants is rather limited and will not justify the large investment that is required before a return on investment can be expected after the registration.

Other chemical options include methyl iodide, phosphine (Ertürk et al., 2018), fumigation under hermetic vacuum (Kumar et al., 2017), phosphine under low pressure (Athanassiou et al., 2016; Şen *et al*., 2015), methyl isothiocyanate (MITC) (Ducom, 1994) and carbon dioxide (CO2), ethane dinitrile (EDN) (Thalavaisundaram and McConville, 2017; Hnatek *et al*., 2018), ozone (Grisales *et al*., 2017; Hansen et al., 2014; Işikber et al., 2015; Pandiselvam *et al*., 2017; Subramanyam *et al*., 2014), inert atmospheres based on nitrogen or carbon dioxide (Vassilakos *et al*.,2019; Sakka *et al*., 2022), hermetic storage (De Bruin *et al*., 2014; Murdock and Baributsa, 2014; Navarro and Navarro, 2014; Prasantha *et al*., 2014), hermetic storage and heat (Bruin *et al*., 2014), nitrogen and heat (Athanassiou et al., 2017), nitric oxide (Liu *et al*., 2017), chlorine dioxide (Han *et al*., 2016; Xinyi *et al*., 2017), carbonyl sulfide (COS) (Desmarchelier, 1994), as well as monoterpenoids (Sağlam and Özder, 2013). Use of essential oils (Guo *et al*., 2016; Kostyukovsky *et al*., 2016) is a further option for partial replacement of MB-use. These oils and extracts of various species of plants and their leaves, branches and fruits [better their active compounds] can be considered as possible candidates for new insecticides or repellents (Alkan *et al*., 2018; Babarinde *et al*., 2017; Campolo *et al*., 2014; 2018; Ertürk *et al*., 2017b;

Nenaah, 2014; Oboh *et al*., 2017), and diatomaceous earths (Ertürk *et al*., 2017a; Sağlam *et al*., 2017a; 2017b; Gultekin *et al*., 2018; Şen *et al*., 2019).

It should not be overlooked, that the essential oils, gained from various plants around the world [varying often in composition from year to year], contain various active compounds, suitable for repelling and control of pest insects and mites. The critical steps, to make these oils or better the individual effective compounds accessible for the application in the market, comprise tedious investigations and fastidious paperwork with administrators following the high standards of use of toxic chemicals. All these presuppositions have to be carried out and fulfilled to obtain the necessary registrations for practical use of these compounds. The same requirements apply for "natural" and synthetic poisons.

7.2.2 Physical Measures

Adoption of nonchemical but physical measures like application of heat (including the heat production by combustion of carbon containing sources, electrical heat, irradiation with gamma ray or electromagnetic waves, infra-red, high frequency), cold and percussion (entoleter) are usually part of an Integrated Pest Management (IPM) system and has been introduced widely for pest control in SC. Also, microwaves, radio frequency (Uraichuen *et al*., 2014) or ionizing radiation, have been investigated for their suitability to replace MB in various application fields. Use of irradiation as a phytosanitary treatment has increased with an undetermined part of this volume directly replacing methyl bromide fumigation (Mansour, 2016). Also, radio frequency is discussed for the treatment of infested dates (Pegna *et al*., 2017).

7.2.3 Biological Measures

The combination of macro- and microbiological antagonists in combination with various traps for early detection - monitoring of pest development, location of the infestation source and testing of efficacy after the control measures -, intensive cleaning (sanitation) and other measures were also introduced within IPM schemes for structures and commodities. In Europe - especially in Germany - and in the US, parasitic wasps and predators now comprise a significant part of pest management programs for facilities and stored products (Reichmuth, 2007).

Haustein *et al*. (2019) investigated larvae and adults of the clariid beetle *Korynetes caeruleus* for the possible use as antagonist for *Anobium punctatum*. The chalcid wasp *Antrocephalus mitys,* cultivated on *Tenebrio molitor,* served for research on its possible role in biological control of *Ephestia cautella* (Pereira *et al*., 2013). Eliopoulos (2019) presented life table parameters of the parasitoid *Cephalonomia tarsalis* and its host, the stored grain pest the sawtoothed grain beetle *Oryzaephilus surinamensis*. Biological control is applied worldwide during pre-harvest for arthropod pest management in a number of commercial crops. In comparison, biological control is not yet considered an option during the post-harvest processing chain, except in few examples in some countries. The residues of dead antagonists and dead pests in the food presents a residue problem. For material protection against *Anobium punctatum*, Auer *et al*. (2021) proposed the parasitoid wasp *Spathius exarator.*

7.2.4 Fields of Applications of MB in Stored Product and Structure Control and Alternatives

In all other Parties of the Montreal Protocol, MB use for pest control in SC has completely been phased out and replaced by alternatives. Table 7-1 shows examples of key alternatives to MB implemented around the world for pest control in structures and commodities.

TABLE 7-2: HISTORICAL KEY USES OF MB, PEST ORGANISMS AND PRESENT REPLACING ALTERNATIVES

Former Key use of MB in structures and commodities	Typical pests	Alternatives now in place
Stored Grain, flour mills, feed mills	Pyralid moths, *Tribolium* spp, *Cryptolestes* spp., *Oryzaephilus surinamensis,* *Cryptolestes ferrugineus*	Sulfuryl fluoride (SF), heat, biological antagonists like parasitoid wasps*, intensive cleaning, contact insecticides, mass trapping, cold, ethyl formate (EF) *****, Integrated Pest Management (IPM)
Historic and cultural buildings (including churches)	Wood-destroying pests (e.g., *Anobium punctatum*, *Hylotrupes bajulus*, *Lyctus brunneus*)	SF, Carbon dioxide (CO_2) ***, nitrogen (N_2) ***, hydrogen cyanide (HCN)
Cereal grain and similar commodities in bag stacks	Cosmopolitan grain insect pests (e.g., *Sitophilus* spp., *Tribolium* spp., Pyralid moths)	Phosphine PH_3), hermetic storage***, parasitoid wasps* (example: *Lariophagus distinguendus*, *Habrobracon hebetor*, *Trichogramma evanescens*), deltamethrin, cyfluthrin or other contact insecticides****, diatomaceous earth****
Cereal grain and similar commodities in bulk	Cosmopolitan grain pests (e.g., *Oryzaephilus surinamensis*, *Rhyzopertha dominica*, *Sitophilus* spp. *Sitotroga cerealella*)	PH_3, contact insecticides****, cooling, CO_2 and/or N_2 and hermetic storage, SF
Nuts	Pyralid mothss, *Oryzaephilus* spp.	SF, PH_3, trapping**
Dried fruit	Pyralid moths, *Carpophilus* spp.	SF, PH_3, EF *****, trapping**
Spices	Pyralid moths, *Stegobium paniceum*	Irradiation, PH_3, cold, CO_2 under high pressure (20 bar)
Houses and other structures with wooden components	Wood destroying pests including *Anobium punctatum*, *Hylotrupes bajulus*, *Lyctus brunneus*, Drywood termites	SF, heat (limitations with sensitive infested artefacts, insecticide treatments (limitations with penetration)
Artefacts (e.g., books, art works with wooden frames, basketwork, carpets, historic uniforms, furs, skulls)	General pests including clothes moths, dermestid beetles, wood borers, *Lepisma saccharina*	N_2, CO2, heat, cold

* Appropriate parasitoid wasps and predators are comprehensively mentioned and described in Reichmut *et al.*, 2007.

** Trapping per se is not a control method, but serves for localisation of hot spots of pests and determination of starting points for control measures

*** The use of CO_2 and/or N_2 to create atmospheres with low residual oxygen content is widely used in material protection for the disinfestation of sensitive artefacts. The application of CO_2 under pressure of about 20 bar in steel chambers presents the opportunity of achieving full control of pest insects and mites within a few hours for instance in infested spices and animal feed. Also, the efficacy of long hermetic storage of grain in closed systems relies on the efficacy of enclosed atmospheres with low residual oxygen content, created by the respiration of stored seeds and of pest insects inside.

**** contact insecticides, diatomaceous earths, extracted oils from plants suffer in their efficacy from bad penetration into stored products. They are not per se an alternative for gaseous molecules like MB with optimal

penetration characteristics. They can serve for control of pests outside the grain kernels and protect with their coated surfaces against later emerging larvae and adults.
***** Ethyl formate has appropriate features for some areas of application but suffers from limited availability due to lack of registration in most countries, apart from New Zealand and Australia.

7.3 Regulatory Considerations

Many commercial companies, researchers and governments have undertaken significant efforts to conduct research, apply for registration, and make alternatives available to users. However, the registration of chemicals for pest control, including MB, is under continuous review in many countries and the number of registered active compounds has been reduced in many countries due to the revision of their negative effects on human health and the environment.

Additional registration issues arise when treatments are needed on food commodities or where treatments used in food processing buildings might transfer critical residues to food because the maximum residue limits (MRLs) for the residual chemicals must also be registered in importing countries. In the Republic of South Africa (RSA), until recently, no fumigant alternatives to methyl bromide were registered for mills and houses. However, as previously mentioned, registration of sulfuryl fluoride has been released in January 2018 and the registration process for ethylene dinitrile (EDN) is under way. This gas is also in the hand of DRASLOVKA with prospects to be available in the future for various fields of application in several countries. At present, there are field trials with logs for exportation and disinfestation running in New Zealand.

7.4 Overview on the Yearly Reduction of MB-Use in South Africa

During the last four years, only one Party (the Republic of South Africa, RSA) was requesting a CUE for further use of MB for pest control in empty grain mills (from 2018 to 2021) as well as for the control of insect pests in infested attics of dwellings with wooden parts in the roof structure (dwellings, churches).

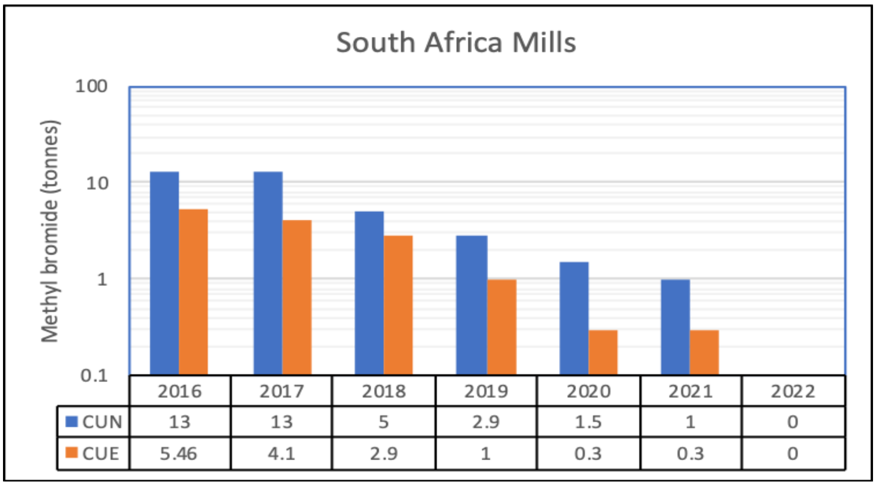
The exemptions for use of MB in the Republic of South Africa over the past years relate to treatments of some grain mills and for some houses (dwellings and churches) infested by wood-destroying pests, particularly drywood termites. The nominations reflected that equally effective and economically feasible alternatives were not available. Later, SF was registered in RSA, and is now gradually more and more replacing the uses of MB.

The remaining amount of MB, nominated by this Party as Critical Use Nomination (CUE) for commodity and structure, was 50 t for use in 2018 for disinfestation of flour mills and houses. The exemption accepted by the Parties for use in this year (CUE) was a reduced amount of 2,9 t for mills and 42,75 t for houses. No more MB was requested by the Party for use in 2022 for the disinfestation of mills. The CUEs for this sector dropped from 2.9 t, granted for use in 2018 for mills, to 0.3 t for 2021 (see figure 7-1).

For houses, the nominations by the Party dropped from 45 t for use in 2018 to 20 t for use in 2023. The recommendation by MBTOC in 2022 for use in 2023 was a slightly reduced amount of 19 t. This upcoming decision over the CUN is indicated by † at the year 2023 in the table in figure 7-2. The final decision by the Parties on this nomination is expected in November of 2022.
No nominations were received for 2022, due to the occurrence of the corona virus.

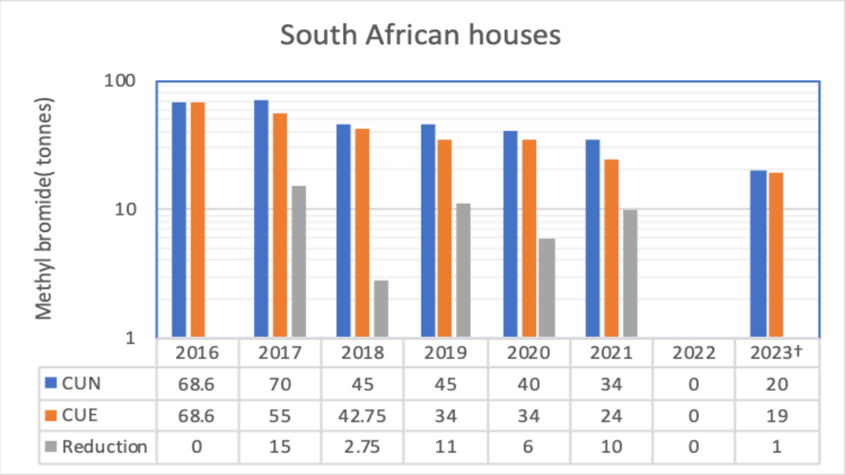
The figures 7-1 and 7-2 include information on some previous years, to illustrate the developments in the respective sectors and the efforts by the Party to reduce the amounts of MB for disinfestation. The figures present data of nominations for use in the respective years for disinfestation of mills and houses as well as the data on the final decisions of the Parties as CUE.

Fig. 7-1: CUN and CUE for South African Flour mills from 2016 to the final date of 2022, when RSA stopped their nomination for this sector.



	2016	2017	2018	2019	2020	2021	2022
■ CUN	13	13	5	2.9	1.5	1	0
■ CUE	5.46	4.1	2.9	1	0.3	0.3	0

Fig. 7-2: CUN and CUE for South African houses from 2016 to 2023



	2016	2017	2018	2019	2020	2021	2022	2023†
■ CUN	68.6	70	45	45	40	34	0	20
■ CUE	68.6	55	42.75	34	34	24	0	19
■ Reduction	0	15	2.75	11	6	10	0	1

The parties endorsed the proposed reduction and by MBTOC and approved 19t of MB as a CUE for use in 2023 at their 34th MOP in November 2022.

Comparing the values for the two columns (reduction) shows clearly the achievements of the yearly assessments of MBTOC in finding alternatives for parts of the nominations and negotiate them with the nominating Party. Together with TEAP and the Parties, significantly reductions from nominated to granted amounts of MB have been achieved.

7.5 Summaries of the alternatives for the remaining CUNs for exempted use of MB

7.5.1 Summary of alternatives for mills

Disinfestation of mills, empty or with residual grain and/or flour presented the biggest challenge for the quick phase out of MB in SC worldwide. Disinfestation of structures, single premises of more than 100,000 m³ in capacity, often required huge amounts of MB to achieve rapid and thorough pest control including all developing stages of insects, mites and rodents.

Presently, flour mills in many countries around the world, such as the Philippines, Malaysia, Indonesia, the United States, and the European Union, use partially heat as well as IPM as an alternative to MB fumigation. Deep cleaning, together with residual spraying and misting of insecticides are used for controlling insect pests. Pheromone traps are used for early detection of new grain pest infestations. In countries like the Philippines, Thailand, Singapore, and Malaysia where phosphine is the only viable fumigant available, initiatives are under way to register SF, which will expand the very limited pest management options available. In the United States, sometimes cold air is applied over the top of grain bins to reduce the re-infestation potential during storage, as most infestations occur near the top of the silos or grain storage bins.

SF was well known for pest control against wood boring pests long before becoming an option for mill disinfestation, developed in the USA in the 1990s by its registration holder, DowAgrosciences (Schneider and Hartsell, 1999). Researchers from many countries took part in this process, showing the efficacy of SF under various climatic conditions against various pest insects and mites, both in laboratory and field trials. Residue formation was also studied, showing that this compound had limited properties as a commodity treatment. For example, its weak efficacy against some insect eggs required high dosages preferably at high temperatures (above 25 °C) (see also the special report in the Assessment Report 2018 of MBTOC on this subject). Nevertheless, this compound, where registered, is a key replacement for MB for the treatment of mills and other structures.

In the United States, Europe and other countries or regions, use of heat to control insect pests in structures was actively investigated (Beckett *et al*., 2007). This technique was well known and in use for controlling wood destroying insects in wooden parts of attics, so in many countries the expertise and technical gear was available and was easily adapted for the disinfestation of empty structures like flour mills. Cost wise, heat is more expensive than MB (about 2 $ instead of 1 $ per m^3) but is still an effective method, which became more interesting as the price of MB increased. Limitations of this technique include sensitivity of wooden and plastic parts of buildings to water loss, slow heating of crevices in concrete surfaces where insects may hide, and energy consumption including its relation to global warming. Still, this method has potential and is often applied locally to infested machinery or parts of buildings. Infrared irradiation and other electromagnetic means can be used to produce heat.

The combination of thorough cleaning, use of contact insecticides or massive release of parasitic wasps as pest antagonists has become a mainstay of pest control for structures such as flour mills. Most often, all commodities within the mills, (i.e., raw grain or flour in bulk, in silos or packed), are removed in advance, as they can be possible sources of re-infestation (or as a matrix for residue formation if SF is used) and to ensure that wasps have good access to the remaining pests. Other fumigants such as hydrogen cyanide and ethyl formate, have been introduced into the market to some degree.

Full site MB fumigation of flour mills has been discontinued in all countries, also 2022 in RSA. Where full site treatment is conducted, periodic applications with heat or alternative other fumigants, mainly SF (Drinkall *et al*., 1996, 2003; Ducom *et al*., 2003; Reichmuth *et al*., 2003) and hydrogen cyanide (Rambeau, 2001) are carried out. Alternative targeted approaches may in some circumstances provide adequate control (Belda *et al*., 2011).

Schuh *et al*. (2008) described in detail the combined use of SF and heat in a big mill in Germany. By applying the fumigant at elevated temperatures, a significant reduction of SF emission was possible since the increased metabolic rate of the pest insects and all their stages including eggs allowed full control with fairly low ct-products of the fumigant. The computer program FUMIGUIDE - supplied by the registrant - contains the lethality data for various insects and stages for the temperature range between 20°C and 40°C, enabling the fumigator to adjust the dosage to the target temperature within the treated premise.

MBTOC considers that full site heat treatments [the premises should not be larger than 40,000 m^3, due to logistic limitations of providing the necessary energy] may be similar in cost to MB use, with moderate capital investment requirements. Heat treatments may also be used to treat particular enwrapped machines, difficult to treat by other methods.

In general, effective pest control in mills requires a combination of measures including localised heat treatment, fumigation with hydrogen cyanide (registered in Europe (Stejskal *et al*., 2017), phosphine or sulfuryl fluoride, as local registration and circumstances permit, plus various insect control measures applied as an IPM system (hygiene, thorough cleaning, HACCP-systems, monitoring pests with traps, etc.). Pest control intervention may be guided by appropriate pest monitoring.

Changing from an established system of periodic routine MB treatment requires time to trial, refine and implement; changes to the mill and machinery structure may be needed to remove pest harbourage as part of the IPM system; MBTOC has accounted for this when assessing CUNs. IPM measures, cleaning and sanitation, as well as spraying of insecticides, full site heat disinfestation of mills smaller than 40,000 m^3 and localised heat treatment of infested machinery in larger mills, should lead to a reduced requirement or even elimination of full site fumigations.

Careful inspection of imported grain is essential beacuse if insects are intercepted separate phosphine fumigation should be conducted prior to introducing this grain into the mills and the milling process in gastight silo bins. Early detection of insect infestations in grain can be difficult, especially for immature stages of a number of pests that develop and feed inside the grain kernels, easily evading visual analysis in food industries. A number of diagnostic techniques are available for detecting hidden pest infestations, for example the insect fragmen4 test, acoustic devices for feeding stages, near-infrared spectroscopy, ELISA and X-ray image analysis (Hagstrum and Subramanyam, 2014; Hubert *et al*., 2009; Trematerra, 2013). Unfortunately, they carry some limitations in terms of sensitivity and cost-time compromise (Neethirajan *et al*., 2007). Recently, a new molecular approach based on a multiplex PCR has been developed and is commercially available for the detection and identification of most important primary pests of grain (Solà *et al*., 2018).

If fumigations are not sufficiently effective, survivors will multiply quickly reaching high numbers. Results may be improved with appropriate sealing, which can be checked and improved with a gas-loss test prior to fumigation (MBTOC 2002, 2006, 2010, 2014, 2018; Reichmuth, 1990). Full-site mill treatments with heat, sulfuryl fluoride or phosphine are most commonly considered as alternatives to MB treatment to control insect pests worldwide. These measures may not be feasible where sulfuryl fluoride is not registered, where phosphine needs long and costly downtime and may damage sensitive electronic items by corrosion, or where imported equipment is needed to carry out the heating is only available at high capital costs. HCN has been reconsidered as a MB alternative and newly registered for this purpose in countries in Europe (Stejskal *et al*., 2017).

Disinfestation of parts of the building by local use of contact insecticides, biological antagonists and intensive cleaning as elements of integrated pest management is in use where other measures may not be feasible. Entoleters are put in place at the end of the chain of milling grain to obtain and/or ensure insect free products prior to loading the flour into trucks. Alternative integrated systems are practiced in many countries (Bell, 2014).

Heat treatment may be similar in cost to MB, with moderate capital investment requirements (Hofmeir, 1996; 2018; Thermonox; Kroll, 2018; Teich, 1996; Suma, 2019). Pest control in flour mills by heat disinfestation). Heat treatments may also be used to treat those machines that are difficult to fully clean by other methods.

7.5.2 Summary of alternatives for houses

As described previously, use of SF (where registered) and/or heat are the main adopted alternatives for destroying structural pests in houses around the world. The method of choice will strongly depend on the specific pests present. For example, certain termites can be controlled easily with fairly low doses of SF that kill the egg-laying queens (La Fage *et al*., 1982). In many countries termites do not occur and wood boring beetles are the target for control, requiring other conditions for effective control. In the United States, termites and carpenter ants are usually controlled using baits containing a slow acting insecticide (abamectin, boric acid, fipronil, or propoxur), which must be replenished as they deplete and may take a long time to work effectively. If the nest is exposed, it can be treated directly with an insecticide (bifenthrin, cyfluthrin, cypermethrin, deltamethrin, lambda cyhalothrin, or permethrin), often formulated as foams or dusts. If baits are not used, insects in the nest must be exposed to insecticide directly. In addition, it is important to remove possible outdoor sources of infestation (decaying wood such as old stumps, logs, or lumber piles).

Under certain conditions, phosphine may be an efficient alternative to MB, especially when sensitive objects to corrosion like copper containing computers, switches, and other electric and electronic devices can be removed prior to the treatment. For termite control, killing of the queens can be achieved with fairly low concentration x time products (ct-products) of SF, in the range of 500 g h/m^3 (20 g/m^3 for 25 h), if the exposure occurs under gas tight sheets and well-sealed houses. These conditions are commonly known to control drywood termites (Stewart, 1957; Osbrink *et al*., 1987). Fumigation with hydrogen cyanide (Rambeau *et al*., 2001) and even inert atmospheres, like nitrogen and carbon dioxide with low residual content of oxygen, are effectively used under corresponding conditions (Lewis and Haverty, 1996; Reichmuth, 2007). Strang (2014) described in detail the use of heat against pests in cultural property.

Control of wood boring insects with heat, even in heavily infested houses within highly infested areas, has been common practice for many years around the world (Hammond, 2015). Phosphine without added heat, is unlikely to be feasible due to its slower action, with fully effective treatments against wood boring pests taking several days.

In RSA, five target pests are mentioned in the critical use nomination: the West Indian drywood termite *Cryptotermes brevis*; the European house borer *Hylotrupes bajalus*, and the small wood and furniture beetles *Anobium punctatum, Lyctus brunneus* and *Nicobium castaneum*. Lethal ct-levels against these pests differ significantly and are also dependent of temperature in the structure.
For controlling low infestations of drywood termites, infestations of other wood destroying insects, particularly *Hylotrupes bajulus* (wood boring beetles, Ducom *et al*, 2003), or multiple infestations of drywood termite (with or without *Hylotrupes bajulus*) SF is mainly used (MBTOC Assessment reports 1998, 2002, 2006, 2010, 2014, 2019), but also heat. Drywood termite infestations can typically be treated using the ‘search-and-destroy’ system, where access is possible. In this process, the nests are located acoustically, electronically or with detector dogs and eliminated by injecting insecticides. Baiting is not normally used as unlike subterranean termites, drywood termite nest in walls and ceilings and do not touch the soil. Established infestations of *Hylotrupes bajulus*, and other wood boring insects, in structural timber are likely to require full-site treatments.

Alternatives to MB include heat treatments at moderately elevated temperatures around 56°C (Dreger, 2007; Lewis and Haverty, 1996). MBTOC found two suppliers of heat producing machines that are also prepared to demonstrate the technique (Hofmeir, 2018; Thermonox; Kroll, 2018). Riminesi and Olmi (2016) proposed and used localized microwave heating for controlling biodeteriogens on cultural heritage assets.

In RSA, wood destroying insects were found attacking various wooden structures, mainly in houses and residential units (2,560 facilities and houses, mainly brick, mortar and iron structures with wooden frames) located along coastal areas and partly inland. These buildings typically had volumes of 600 m^3 to 850 m^3, but some were much larger. About 75% require complete structure fumigations for about 1,152,000 m^3 and 25% partial fumigations (individual rooms, individual flats, calculated with about 1/5 of a 600 m^3-structure) for 384,000 m^3 leading to 41.47 t plus 3.53 t, resulting in a total of 45 t of MB used. About 200 structures are fumigated per month.

For SF-use, the computer program (FUMIGUIDE, provided by the registrant) will determine the necessary dosage for full control of the specific pest species in the future. Treatments are carried out either on entire houses under PVC 450 µm tarpaulin or on gas-tight sealed parts of structures. Heat treatment, a technique used under similar circumstances in many countries, was regarded by the Party as not feasible due to the high investment associated with importing heating units and excessive running costs compared with MB treatment, as well as poor access of the heat into some parts of the roof spaces. Heat treatment for control of wood boring pests is also not acceptable for obtaining a “Free of Insects Certificate”, required for a sale agreement to proceed. This certificate is only produced after inspection from pertinent authorities.

After registration, sulfuryl fluoride (SF) is now accessible to the market in RSA and fumigation with this product is possible for both houses and mills. As expected, some time was needed to set up supply and training systems, to fully enter with SF into the practice of fumigation. The phase in of SF for mills is now completed, a significant reduction of MB use for treatment of houses can be expected. Figure 7.2 reveals the yearly effort by the Party to phase out MB also from this sector.

7.6 Challenge to keep sulfuryl fluoride as option for methyl bromide in the market

The report comments in detail on the difficulties visible at the horizon in case sulfuryl fluoride loses access to the market. This fumigant is the main replacement gas for MB in very many countries. It is the main control agent in protection of some stored products, wooden artifacts, other infested material of organic origin (e.g., historic uniforms and other clothes, precious artifacts and frames of paintings in museums) and empty structures (e.g., large infested flour and feed mills and factories, public and private houses). In Germany, many churches especially in the Southern part, are infested by wood destroying insects that must be controlled to avoid severe losses of precious cultural heritages. MB had been the fumigant of choice until - due to the decisions of the Montreal Protocol – this gas could effectively be replaced by SF.

The possible alternatives for SF have all serious negative side-effects (personal communication of Dr. Gerhard Binker, oral presentation at the MBTOC meeting in Bonn, 2022). “Application of **liquid wood preservatives** (constraints: contamination, non-acceptable staining). Use of **heat treatments** [constraints: crackling problems of paintings and release of wood-resins during or after heat treatments; cracks and crevices caused by thermal tensions during heat treatments for eradication of woodworms in churches].

Use of other reactive fumigants such as **phosphine**, **hydrogen cyanide**)

Phosphine: constraints: corrosion of silver materials /surfaces caused by phosphine, formation of black silver oxides on filigree silver wire netting and black overlays, formation of silver phosphates: silver pyrophosphate $Ag_4P_2O_7$, and silver metaphosphate AgPO, corrosion of brass- and silver-materials/surfaces caused by phosphine (Brigham, 1998; 1999; Gherdán *et al*., 2014).

Hydrogen cyanide: constraints: formation of alloys of Pb and Zn, corrosion of these metals in organs in churches, formation of brown azulmine acid (= polymeric acid) and other compounds during HCN-fumigations on caustic church walls (Grosser and Roßmann, 1974). Disinfestations of churches with inert gases, like CO_2 and/or N_2 are too expensive (more than 1040 times in comparison to SF, due to very large amounts of gas required during weeks of treatment; also, expensive hardware and logistics are needed. The global warming leads also to increase of control problems due to increasing multiplication of pest insects. Application of liquid wood preservatives / liquid insecticides or heat treatments are no viable methods in churches to control insect pests (woodborers).

PH_3 and HCN (and EDN = C_2N_2) are too corrosive towards metals found in cultural objects. Nitrogen and carbon dioxide atmospheres with low residual oxygen content as fumigants are far too expensive for the treatment of large objects/structures (the needs of hardware and gas are enormous). Only for disinfestation of artifacts in fumigation chambers or in plastic bubbles, this approach seems to be very effective and quite cheap. It has been tried to regain SF from fumigated objects with liquid nitrogen to reduce the emissions int the ambient atmosphere. The necessary amounts of liquid N2 or air is enormous, the apparatus very costly. In addition, only about 50 % of the gas may be regained due to losses, sorption and reaction during the treatment. Also, the recapture and chemical destruction have been tried (Binker and Binker, 2006)."

The use and following emission of SF into ambient air is of concern because of SF has a high Global Warming Potential (GWP) and contributes much stronger than CO_2 to the Global Warming Effects of man-made and emitted gases (Miller *et al*., 2017; Gressent *et al*., 2021). The possible difficulties for further use of this substance in pest control presents a draw back in the replacement of MB, since many fields of former use of MB would be stripped from the only – formerly judged - "viable and feasible alternative" in many instances being SF. The issue of identifying, evaluating and developing economically feasible alternatives for SF would need to start again.

7.7. References

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8

8. Economic Issues

8.1. Introduction

No CUN has relied solely on an economic argument to establish the infeasability of using alternatives to methyl bromide in the long period of assessment by MBTOC. Nevertheless, Parties have become more conversant over the years in providing the economic data, analyses and information required to conduct rigorous economic assessments. This is also true of the most recent nominations from A5 parties, namely those of Argentina and the Republic of South Africa, as well as from non-A5 parties which includes the Australian and Canadian nominations.

In its 2018 Assessment Report, MBTOC anticipated two changes in the nature of the economic analysis required for the assessment of economic feasibility:

1. First, it was anticipated that the Australian and Canadian Parties may shift emphasis in their CUNs to the issue of economic infeasibility. This turned out to be the case with both nominations, although neither relies exclusively on an argument of economic feasibility.
2. Second, MBTOC anticipated that it may be asked to comment on the type(s) of economic evaluation that will be required with QPS uses of methyl bromide. This would include analysis of:

    - ➢ The costs of eradication of exotic or invasive species of plants or pests
    - ➢ The economic costs of exposure to exotic or invasive species of plants or pests
    - ➢ The costs of trade distortions created by non-tariff barriers.

Each of these is discussed in turn below, after a summary of the process of economic analysis used to date by MBTOC.

8.2 Economic analysis of the adoption of alternatives to MBTOC

No CUN has to date relied solely on an argument of economic infeasibility to argue for an exemption. Nevertheless, MBTOC analyses any arguments and calculations about the economics of the use of methyl bromide alternatives put forward by a Party because it is always possible that MBTOC may recommend against an exemption on technical grounds but find that economic factors mitigate against the use of alternatives. This is in addition to the conventional notion that the use of an alternative to methyl bromide may be technically feasible, but that it may turn out to be economically infeasible.

As noted in previous Assessment Reports, it is sufficient in most cases to use **partial budgets** to assess economic feasibility. This is reflected in the fact that most peer-reviewed literature that addresses economic feasibility makes use of this methodology. Recent examples include Wade, et al. (2020) Athearn *et al.* (2021) and Donahoo *et al.* (2021).

However, there are circumstances where more sophisticated analyses could be required, hence the economists' toolkit contains extra needs:

1. The simplest extension to partial budgeting is to conduct a sensitivity analysis. Partial budgeting and the financial rations (such as the internal rate of return, liquidity ratios, etc.) assist in finding which revenue and/or cost factors have the biggest influence on the "bottom line" of an industry or an enterprise. **Sensitivity analysis** on these factors (e.g. by increasing and/or decreasing the value of an input by a few percentage points at a time) shows whether more accurate data is essential (see e.g. Wolverton, 2014). For example, if the use of methyl bromide and/or its alternative constitutes a very small share of the total cost of production, it is unlikely that a doubling in this cost will materially affect the bottom line.
2. A budget represents a snapshot of the cost of production and the revenues flowing from that production process at a single point in time. However, the price of all production inputs and of all products that are produced change randomly all the time in a manner that is probabilistic - termed a stochastic process. Economists measure **the supply of and demand for** goods and services econometrically to predict the direction in which these changes are likely to occur. This can be done in a partial (e.g. Li *et al.*, 2020) or even a general equilibrium analysis (e.g. Miller and Mann, 2017)
3. Finally, there are often 'invisible' costs and or revenues involved in production processes, in the sense that they are not part of the decision process for producers in production (e.g. the pollution caused by their actions, the effect on the ozone layer of using methyl bromide), or of consumers in consumption (e.g. the benefits to the ozone layer of reduced use of methyl bromide). Economists have a range of techniques to estimate what prices would have been (termed **'shadow prices'**) had these factors actually been taken into account – techniques that fall under the broad heading of 'willingness to pay' (e.g. Antle and Ray, 2020; Papyrakis and Tasciotti, 2021; Wijeyekoon et al. (2021). Such analyses can also be done at a regional or global level (e.g. Zambrano-Monserrate *et al.*, 2021).

These techniques are not always easy to use, and they invariably require a lot of data that is not often forthcoming, hence the simplest techniques should be used where appropriate.

8.3 Current critical use nominations: are economic arguments being used?

The current CUNs by Australia and Canada for the use of methyl bromide in the production of strawberry runners have both been argued on technical grounds to date, but strong economic arguments have also been put forward by both Parties.

8.3.1. Australia

Australia has consistently argued that producers have been able to pass on the additional cost of using methyl bromide alternatives to buyers during the migration of the nucleus, foundation and mother stock to soilless culture practices. These additional costs arise largely from the additional labour requirement in a country with high labour costs. However, the Party has also argued that this pass-on in price was not possible in the final phase, i.e. in migrating from mother stock to certified runners produced in open fields before dispatch to fruit growers, as in this case the labour requirement increased exponentially. Sufficient data have been provided by the Party to support this argument. Notwithstanding, the Party has based its nomination on the prospect of having mixtures of MI + Pic registered and on further research into the use of microwave technology rather than on an economic argument.

8.3.2. Canada

The Party has provided data on the cost of migrating the production of G2 runner tips from open field to the Haygrove soilless system, arguing that it is an economically infeasible alternative to the use of methyl bromide in the circumstances of the nomination. However, this cannot be established in the absence of a partial budget. The Party has also provided data on the use of "Botanicoir Precision Plus" grow bags (used in a greenhouse), in this case in the form of a preliminary partial budget analysis. The analysis shows that a substantial increase in the productivity of this stage (a technical rather than an economic issue) is required for it to be economically feasible. This is because there is no expectation that this growing system will produce higher quality G2 runner tips, therefore the runners will not fetch a higher price in the market. The only way to recoup the higher cost, therefore, is to improve productivity, which in this case means the number of plants that are propagated in order to achieve a lower per plant cost of production. Substantial progress has been made in achieving such productivity gains, and the Party argues that the grower should be able to reduce these costs and increase output given more experience. As a result, the nomination is still based in a technical rather than an economic argument.

8.3.3. Summary

While both Australia and Canada have provided information in support of an argument for economic infeasibility, they are both still essentially basing their nominations on regulatory issues (Australia) and on the need for productivity improvements (Canada), neither of which are economic issues. Neither of the other two nominating parties (Argentina and South Africa) have relied on economic arguments.

8.4 New departures: the economics of QPS

As shown above, it is possible that MBTOC will at some point in the future be asked to comment on issues such as:

- What are the costs of eradication of exotic or invasive species of plants or pests?
- What are the economic costs of exposure to exotic or invasive species of plants or pests?
- What are the costs of trade distortions created by non-tariff barriers?

Each of these is discussed briefly.

8.4.1. The costs of eradicating exotic or invasive species

It may seem evident that simple budgeting procedures could be used to estimate the costs of eradication of alien invasive species of any kind (animal, vegetable, insects, etc.), but it should be as evident that the cost cannot be restricted to only the physical costs of removal of the species for a number of reasons:

1. The removal of alien invasive species also brings about a range of benefits, especially in terms of peoples' livelihoods, which have to be taken into account in calculating the net cost. This is complicated by the fact that many of these benefits are not observable in the sense that a monetary value can be attached to them, hence shadow prices have to be estimated (see for example Ngorima and Shackleton, 2018; Shackleton *et al*., 2018, Shrestha *et al*., 2019).
2. Invasive species spread in different ways over space and time, and have different environmental and social impacts, hence decisions must be taken regarding which species to eradicate first or when to eradicate what, and how should it be done (e.g. Pepin *et al*., 2020). These decisions will affect the cost of eradication, hence such priorities must be in place before the implementation of eradication procedures. Different techniques can be employed to estimate these different impacts, for example cost-benefit analysis (Courtois et al., 2017; Ngorima and Shackleton, 2018; Reyns *et al*., 2018); community participation methods (Shrestha et al., 2019); algorithms to predict where invasions will take place (Fournier *et al*., 2019); operations research techniques (Büyüktahtakın and Haight, 2018); and econometric techniques (Baker *et al*., 2018; Jardine and Sanchirico, 2019).

8.4.2. The economic costs of exposure to exotic or invasive species

Leroy et al. (2021) describe InvaCost, a global database aimed at facilitating estimates of the costs to society and the environment of invasive alien species. They argue that accessing such databases is complicated and time-consuming, hence they propose open access software solutions to overcome this problem. Volume 67 of the Journal *NeoBiota* has a series of applications using this database from around the world (see Zenni *et al*., 2021) while Diagne *et al*., (2021) also estimate the global costs.

Other applications include aquatic invasive alien species (e.g. Cuthbert et al., 2021); crustaceans (Kouba et al., 2022); rats, mosquitoes, dogs, rabbits, starlings, fruit flies, pigs, and moths (Ahmed *et al*., 2021); ants (Angulo *et al*., 2022[9]); plants (Van Wilgen et al., 2020); terrestrial invertebrates (Renault, 2022); and exotic grasses (Assis *et al*., 2020) among others.

8.4.3. The costs of trade distortions created by non-tariff barriers

In neoclassical economic theory all measures that impact on the free flow of goods and services detract from social welfare and are therefore undesirable. However, it is not always easy to differentiate between measures that distort trade unfairly and those that do so justifiably. In this regard, the OECD[10] defines them as follows:

> *The term "non-tariff measures" (NTMs) covers a diverse set of measures in terms of purpose, legal form and economic effect. NTMs comprise all policy measures other than tariffs and tariff-rate quotas that have a more or less direct impact on international trade. They can affect the price of traded products, the quantity traded, or both.*
>
> *These measures can be broadly divided into two groups. The first type, called "technical" measures, includes regulations, standards, testing and certification, primarily sanitary and phytosanitary (SPS) and Technical Barriers to Trade (TBT) measures. The second type, called "non-technical" measures, includes quantitative restrictions (quotas, non-automatic import licensing), price measures, forced logistics or distribution channels, and so on.*

The measurement of the trade impacts of these measures has received considerable attention in the literature, but the techniques are well known. For example, Cadot et al., 2018 have estimated the trade effects of such measures for some 5 000 traded goods and 80 countries using econometric techniques. Furthermore, UNCTAD and the WTO (no date) provide a user's guide to the measurement of these effects.

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Annex 1

Annex 1. Methyl Bromide Technical Options Committee - Committee Structure

MBTOC structure as at 31 December 2022

Co chairs

Ian Porter	La Trobe University Australia
Marta Pizano	Consultant Colombia

Subcommittee chairs, chapter lead authors for this Assessment

- **Chapter 1** - Executive summary
- **Chapter 2** - Introduction to the assessment - Lead authors, *Marta Pizano, Ian Porter.*
- **Chapter 3** - Methyl Bromide production and consumption (controlled uses) - lead authors, *Marta Pizano, Alejandro Valeiro.*
- **Chapter 4 -** Methyl Bromide Emissions. Lead authors *Ian Porter, Jonathan Banks* (Paul Fraser from SAP contributed to some sections)
- **Chapter 5 –** Quarantine and Pre-shipment – Lead authors *Cristoph Reichmuth, Marta Pizano, Ayse Ozdem, Ken Glassey*
- **Chapter 6 -**Alternatives to Methyl Bromide for soil treatment – lead authors *Mohamed Besri*, *Tim Widmer, Ian Porter*
- **Chapter 7 -** Alternatives for Treatment of Post-Harvest Commodities and Structures –*Christoph Reichmuth, Ayse Ozdem*.
- **Chapter 8 –** Dconomic issues – Lead author *Nick Vink*

Committee contact details and Disclosure of Interest

To assure public confidence in the objectivity and competence of TEAP, TOC, and TSB members who guide the Montreal Protocol, Parties to the Protocol have asked that each member disclose proprietary, financial, and other interests. Disclosures of Interest (DOI) are posted at the Ozone Secretariat website and are updated as necessary, once a year at minimum. They can be accessed at http://ozone.unep.org/en/disclosure_of_interest.php?body_id=6&committee_id=6

Table A-1 below contains the lists of MBTOC members at December 31st, 2022.

TABLE A-1: MBTOC MEMBERS AS AT DECEMBER 31ST, 2022

Chairs		**Affiliation**	**Country**
1. Ms. Marta Pizano	F	Consultant, Hortitecnia Ltda.	Colombia, A5
2. Prof. Ian Porter	M	La Trobe University	Australia, Non-A5
Members		**Affiliation**	**Country**
3. Prof. Aocheng Cao	M	Institute of Plant Protection, Chinese Academy of Agricultural Sciences	China, A 5
4. Dr. Jonathan Banks	M	Consultant	Australia, Non-A5
5. Prof. Mohamed Besri	M	Dept. of Plant Pathology, Institut Agronomique et Vétérinaire Hassan II	Morocco, A5
6. Mr. Fred Bergwerff	M	ECO2, Netherlands	Netherlands, Non-A5
7. Ayse Ozdem	M	Ministry of Agriculture	Turkey, A-5
8. Mr. Ken Glassey	M	Senior Advisor Operational Standards Biosecurity New Zealand, Ministry of Agriculture and Forestry Wellington	New Zealand Non- A5
9. Mr. Alfredo Gonzalez	M	Fumigator	Philippines, A5
10. Dr Tim Widmer	F	United States Department of Agriculture	USA, Non-A5
11. Mr. Takashi Misumi	M	Quarantine Disinfestation Technology Section, Ministry of Agriculture, Forestry and Fisheries MAFF	Japan, Non A5
12. Prof. Christoph Reichmuth	M	Professor, Humboldt University Berlin. Retired from JKI Germany	Germany, Non-A5
13. Mr. Jordi Riudavets	M	IRTA-Department of Plant Protection.	Spain, Non-A5
14. Mr. Akio Tateya	M	Technical Adviser, Japan Fumigation Technology Association	Japan, non-A5
15. Mr. Alejandro Valeiro	M	National Project Coordinator, National Institute for Agriculture and Technology, Tucumán	Argentina, A 5
16. Prof. Nick Vink	M	University of Stellenbosch, Department of Agricultural Economics	South Africa, A 5
TOTALS	16		F= 2 M = 14 A5= 7 non A5 = 9

Annex 2 –Lethal conditions to control various species and developmental stages of pest insects (Reichmuth, 2000)

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve); jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Acanthoscelides obtectus aL	1	0	99	9	25
Acanthoscelides obtectus aL	1	0	99	5	32
Acanthoscelides obtectus aL	2	0	98	11	25
Acanthoscelides obtectus aL	2	0	98	9	32
Acanthoscelides obtectus aL	3	0	97	9	25
Acanthoscelides obtectus aL	3	0	97	7	32
Acanthoscelides obtectus aL	0	0	100	8.1	25
Acanthoscelides obtectus aL	0	0	100		25
Acanthoscelides obtectus aL	0	0	100	3.3	32
Acanthoscelides obtectus aL	2.4	88	9.6	5	25
Acanthoscelides obtectus aL	2.4	88	9.6	5	32
Acanthoscelides obtectus aL*	6	70	24	8	25
Acanthoscelides obtectus aL*	6	70	24	5.4	32
Acanthoscelides obtectus aL*	8	60	32	10	25
Acanthoscelides obtectus aL*	8	60	32	5.5	32
Acanthoscelides obtectus aL*	10	50	40	15	25
Acanthoscelides obtectus aL*	10	50	40	13	32
Acanthoscelides obtectus E	0	100	0	1	25
Acanthoscelides obtectus E	0	100	0	1	32
Acanthoscelides obtectus E	1	0	99	1	25
Acanthoscelides obtectus E	1	0	99	1	32
Acanthoscelides obtectus E	2	0	98	2	25
Acanthoscelides obtectus E	2	0	98	1	32
Acanthoscelides obtectus E	3	0	97	4	25
Acanthoscelides obtectus E	3	0	97	1	32
Acanthoscelides obtectus E	0	0	100	3.5	25
Acanthoscelides obtectus E	0	0	100		25
Acanthoscelides obtectus E	0	0	100	1.4	32
Acanthoscelides obtectus E	2.4	88	9.6	1	25
Acanthoscelides obtectus E	2.4	88	9.6	1	32
Acanthoscelides obtectus E	6	70	24	3	25
Acanthoscelides obtectus E	6	70	24	1	32
Acanthoscelides obtectus E	8	60	32	5	25
Acanthoscelides obtectus E	8	60	32	3	32
Acanthoscelides obtectus E	10	50	40	5	25
Acanthoscelides obtectus E	10	50	40	3	32
Acanthoscelides obtectus I	0	100	0	1	25
Acanthoscelides obtectus I	0	100	0	1	32
Acanthoscelides obtectus I	1	0	99	2	25
Acanthoscelides obtectus I	1	0	99	1	32
Acanthoscelides obtectus I	2	0	98	2	25
Acanthoscelides obtectus I	2	0	98	1	32

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve); jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Acanthoscelides obtectus I	3	0	97	3	25
Acanthoscelides obtectus I	3	0	97	2	32
Acanthoscelides obtectus I	0	0	100	1	25
Acanthoscelides obtectus I	0	0	100		25
Acanthoscelides obtectus I	0	0	100	1	32
Acanthoscelides obtectus I	2.4	88	9.6	1	25
Acanthoscelides obtectus I	2.4	88	9.6	1	32
Acanthoscelides obtectus I	6	70	24	1	25
Acanthoscelides obtectus I	6	70	24	1	32
Acanthoscelides obtectus I	8	60	32	1	25
Acanthoscelides obtectus I	8	60	32	1	32
Acanthoscelides obtectus I	10	50	40	3	25
Acanthoscelides obtectus I	10	50	40	1	32
Acanthoscelides obtectus jL	1	0	99	5	25
Acanthoscelides obtectus jL	1	0	99	3	32
Acanthoscelides obtectus jL	2	0	98	7	25
Acanthoscelides obtectus jL	2	0	98	5	32
Acanthoscelides obtectus jL	3	0	97	7	25
Acanthoscelides obtectus jL	3	0	97	5	32
Acanthoscelides obtectus jL	0	0	100	3.3	25
Acanthoscelides obtectus jL	0	0	100		25
Acanthoscelides obtectus jL	0	0	100	1,4	32
Acanthoscelides obtectus jL	2.4	88	9.6	3	25
Acanthoscelides obtectus jL	2.4	88	9.6	3	32
Acanthoscelides obtectus jL	6	70	24	5	25
Acanthoscelides obtectus jL	6	70	24	3	32
Acanthoscelides obtectus jL	8	60	32	5	25
Acanthoscelides obtectus jL	8	60	32	3	32
Acanthoscelides obtectus jL	10	50	40	3	32
Acanthoscelides obtectus jL*	10	50	40	6	25
Acanthoscelides obtectus L	0	100	0	3	32
Acanthoscelides obtectus P	0	100	0	6	25
Acanthoscelides obtectus P	0	100	0	4	32
Acanthoscelides obtectus P	1	0	99	9	25
Acanthoscelides obtectus P	1	0	99	5	32
Acanthoscelides obtectus P	2	0	98	11	25
Acanthoscelides obtectus P	2	0	98	7	32
Acanthoscelides obtectus P	3	0	97	11	25
Acanthoscelides obtectus P	3	0	97	9	32
Acanthoscelides obtectus P	0	0	100	7.3	25
Acanthoscelides obtectus P	0	0	100		25
Acanthoscelides obtectus P	0	0	100	3.4	32
Acanthoscelides obtectus P	2.4	88	9.6	5	25
Acanthoscelides obtectus P	2.4	88	9.6	3	32
Acanthoscelides obtectus P*	6	70	24	10	25
Acanthoscelides obtectus P*	6	70	24	7	32
Acanthoscelides obtectus P*	8	60	32	9	25

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Acanthoscelides obtectus P*	8	60	32	5.3	32
Acanthoscelides obtectus P*	10	50	40	15	25
Acanthoscelides obtectus P*	10	50	40	7	32
Acanthoscelides obtectusL	0	100	0	4	25
Anobium punctatum L	0	0	100	29.7	20
Anobium punctatum L	0	0	100	35	16
Anobium punctatum L	0	0	100	28	22
Anobium punctatum L (LD100)	1.1	0	98.9	21	35
Anthrenus verbasci L	0	4	96	3.5	25
Anthrenus verbasci L	0	10	90	2.4	25
Anthrenus verbasci L	0	0	100	5.6	25
Callosobruchus maculatus aL	0	100	0		25
Callosobruchus maculatus aL	0	100	0	4	32
Callosobruchus maculatus aL	1	0	99	11	25
Callosobruchus maculatus aL	1	0	99	7	32
Callosobruchus maculatus aL	2	0	98	11	25
Callosobruchus maculatus aL	2	0	98	9	32
Callosobruchus maculatus aL	3	0	97	13	25
Callosobruchus maculatus aL	3	0	97	11	32
Callosobruchus maculatus aL	0	0	100	8.8	25
Callosobruchus maculatus aL	0	0	100		25
Callosobruchus maculatus aL	0	0	100	3.9	32
Callosobruchus maculatus aL	2.4	88	9.6	4.4	25
Callosobruchus maculatus aL	2,4	88	9.6	2.4	32
Callosobruchus maculatus aL	6	70	24	10.7	25
Callosobruchus maculatus aL	6.	70	24	5.1	32
Callosobruchus maculatus aL	8	60	32	10.4	25
Callosobruchus maculatus aL	8	60	32	5.5	32
Callosobruchus maculatus aL	10	50	40	11.4	25
Callosobruchus maculatus aL	10	50	40	6.4	32
Callosobruchus maculatus E	0	100	0	1	25
Callosobruchus maculatus E	0	100	0	1	32
Callosobruchus maculatus E	1	0	99	3	25
Callosobruchus maculatus E	1	0	99	2	32
Callosobruchus maculatus E	2	0	98	3	25
Callosobruchus maculatus E	2	0	98	2	32
Callosobruchus maculatus E	3	0	97	4	25
Callosobruchus maculatus E	3	0	97	3	32
Callosobruchus maculatus E	0	0	100	3.2	25
Callosobruchus maculatus E	0	0	100		25
Callosobruchus maculatus E	0	0	100	1.3	32
Callosobruchus maculatus E	2.4	88	9.6	1	25
Callosobruchus maculatus E	2.4	88	9.6	1	32
Callosobruchus maculatus E	6	70	24	2	25
Callosobruchus maculatus E	6	70	24	1	32
Callosobruchus maculatus E	8	60	32	3	25
Callosobruchus maculatus E	8	60	32	2	32

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Callosobruchus maculatus E	10	50	40	3	25
Callosobruchus maculatus E	10	50	40	3	32
Callosobruchus maculatus I	0	100	0	1	25
Callosobruchus maculatus I	0	100	0	1	32
Callosobruchus maculatus I	1	0	99	2	25
Callosobruchus maculatus I	1	0	99	1	32
Callosobruchus maculatus I	2	0	98	4	25
Callosobruchus maculatus I	2	0	98	2	32
Callosobruchus maculatus I	3	0	97	5	25
Callosobruchus maculatus I	3	0	97	3	32
Callosobruchus maculatus I	0	0	100	1	25
Callosobruchus maculatus I	0	0	100		25
Callosobruchus maculatus I	0	0	100	1	32
Callosobruchus maculatus I	2.4	88	9.6	1	25
Callosobruchus maculatus I	2.4	88	9.6	1	32
Callosobruchus maculatus I	6	70	24	1	25
Callosobruchus maculatus I	6	70	24	1	32
Callosobruchus maculatus I	8	60	32	2	25
Callosobruchus maculatus I	8	60	32	1	32
Callosobruchus maculatus I	10	50	40	3	25
Callosobruchus maculatus I	10	50	40	2	32
Callosobruchus maculatus jL	0	100	0	4	25
Callosobruchus maculatus jL	0	100	0	3	32
Callosobruchus maculatus jL	1	0	99	7	25
Callosobruchus maculatus jL	1	0	99	5	32
Callosobruchus maculatus jL	2	0	98	9	25
Callosobruchus maculatus jL	2	0	98	7	32
Callosobruchus maculatus jL	3	0	97	9	25
Callosobruchus maculatus jL	3	0	97	7	32
Callosobruchus maculatus jL	0	0	100	8.8	25
Callosobruchus maculatus jL	0	0	100		25
Callosobruchus maculatus jL	0	0	100	3.7	32
Callosobruchus maculatus jL	2.4	88	9.6	3	25
Callosobruchus maculatus jL	2.4	88	9.6	2	32
Callosobruchus maculatus jL	6	70	24	5	25
Callosobruchus maculatus jL	6	70	24	4	32
Callosobruchus maculatus jL	8	60	32	6.2	25
Callosobruchus maculatus jL	8	60	32	3.9	32
Callosobruchus maculatus jL	10	50	40	4.9	25
Callosobruchus maculatus jL	10	50	40	4.2	32
Callosobruchus maculatus L schw B	6	70	24	6.3	27
Callosobruchus maculatus L schw B	1	0	99	6.4	27
Callosobruchus maculatus L schw B	14	30	56	9.3	27
Callosobruchus maculatus L schw B	4	0	96	8.6	27
Callosobruchus maculatus L st B	6	70	24	9.1	27
Callosobruchus maculatus L st B	1	0	99	9.4	27
Callosobruchus maculatus L st B	14	30	56	10.7	27

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Callosobruchus maculatus L st B	4	0	96	14	27
Callosobruchus maculatus P	0	100	0		25
Callosobruchus maculatus P	0	100	0		32
Callosobruchus maculatus P	1	0	99	9	25
Callosobruchus maculatus P	1	0	99	5	32
Callosobruchus maculatus P	2	0	98	9	25
Callosobruchus maculatus P	2	0	98	7	32
Callosobruchus maculatus P	3	0	97	15	25
Callosobruchus maculatus P	3	0	97	11	32
Callosobruchus maculatus P	0	0	100	8	25
Callosobruchus maculatus P	0	0	100		25
Callosobruchus maculatus P	0	0	100	3.9	32
Callosobruchus maculatus P	2.4	88	9.6	4.6	25
Callosobruchus maculatus P	2.4	88	9.6	3.6	32
Callosobruchus maculatus P	6	70	24	10.9	25
Callosobruchus maculatus P	6	70	24	5.5	32
Callosobruchus maculatus P	8	60	32	11.4	25
Callosobruchus maculatus P	8	60	32	5.1	32
Callosobruchus maculatus P	10	50	40	11	25
Callosobruchus maculatus P	10	50	40	6.2	32
Callosobruchus maculatus P schw B	6	70	24	6.6	27
Callosobruchus maculatus P schw B	1	0	99	6.6	27
Callosobruchus maculatus P schw B	14	30	56	9.3	27
Callosobruchus maculatus P schw B	4	0	96	9.1	27
Callosobruchus maculatus P st B	6	70	24	10.8	27
Callosobruchus maculatus P st B	1	0	99	10.4	27
Callosobruchus maculatus P st B	14	30	56	10.7	27
Callosobruchus maculatus P st B	4	0	96	10.8	27
Callosobruchus subinnotatus E	0	0	100	1.25	32
Callosobruchus subinnotatus100 E	0	100	0	1.25	32
Callosobruchus subinnotatus100 I	0	0	100	1	30
Callosobruchus subinnotatus100 I	0	100	0	1	30
Callosobruchus subinnotatus100 I	0	0	100	0.67	32
Callosobruchus subinnotatus100 I	0	100	0	0.67	32
Callosobruchus subinnotatus100 I1day	0	0	100	1	32
Callosobruchus subinnotatus100 I1day	0	100	0	1	32
Callosobruchus subinnotatus100 I3days	0	0	100	0.92	32
Callosobruchus subinnotatus100 I3days	0	100	0	0.92	32
Callosobruchus subinnotatus100 I6days	0	0	100	0.75	32
Callosobruchus subinnotatus100 I6days	0	100	0	0.75	32
Callosobruchus subinnotatus100 L1	0	0	100	3	32
Callosobruchus subinnotatus100 L1	0	100	0	3	32
Callosobruchus subinnotatus100 L3	0	0	100	4	32
Callosobruchus subinnotatus100 L3	0	100	0	4	32
Callosobruchus subinnotatus100 Ll	0	0	100	4	32
Callosobruchus subinnotatus100 Ll	0	100	0	4	32
Callosobruchus subinnotatus100 P	0	0	100	6	32

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Callosobruchus subinnotatus100 P	0	100	0	6	32
Callosobruchus subinnotatus100 pP	0	0	100	6	32
Callosobruchus subinnotatus100 pP	0	100	0	6	32
Corcyra cephalonica E	16	20	94	5.4	15
Corcyra cephalonica E	12	40	48	5.5	15
Corcyra cephalonica E	8	60	32	3.9	15
Corcyra cephalonica E	2	90	8	3.3	15
Corcyra cephalonica E	16	20	94	4.9	25
Corcyra cephalonica E	12	40	48	4.2	25
Corcyra cephalonica E	8	60	32	4.8	25
Corcyra cephalonica E	2	90	8	3.2	25
Dermestes maculatus	0	0	100	2	25
Dermestes maculatus	0	0	100	2	25
Dermestes maculatus	2	0	98	2	25
Dermestes maculatus	0	0	100	2	25
Dermestes maculatus	0	0	100	2	25
Dermestes maculatus	2	0	98	2	25
Dermestes maculatus	0	0	100	2	25
Dermestes maculatus	0	0	100	2	25
Dermestes maculatus	2	0	98	2	25
Dermestes maculatus E	0	0	100	1	25
Dermestes maculatus E	0	0	100	1	25
Dermestes maculatus E	2	0	98	1	25
Dermestes maculatus E	8	60	32	1	25
Dermestes maculatus I	0	0	100	2	25
Dermestes maculatus I	0	0	100	2	25
Dermestes maculatus I	2	0	98	2	25
Dermestes maculatus L	0	0	100	2	25
Dermestes maculatus L	0	0	100	2	25
Dermestes maculatus L	2	0	98	2	25
Dermestes maculatus P	0	0	100	2	25
Dermestes maculatus P	0	0	100	2	25
Dermestes maculatus P	2	0	98	2	25
Dinoderus bifoveolatus I	16	40	44	5.2	30
Dinoderus bifoveolatus I	8	60	32	1.6	30
Dinoderus bifoveolatus I	2	0	98	1.9	30
Dinoderus porcellus I	16	40	44	3.8	30
Dinoderus porcellus I	8	60	32	1.1	30
Dinoderus porcellus I	2	0	98	1.3	30
Ephestia elutella E	16	20	94	7.3	15
Ephestia elutella E	12	40	48	6.4	15
Ephestia elutella E	8	60	32	5.8	15
Ephestia elutella E	2	90	8	5.3	15
Ephestia elutella E	16	20	94	3.6	25
Ephestia elutella E	12	40	48	2.9	25
Ephestia elutella E	8	60	32	2.2	25
Ephestia elutella E	2	90	8	1.7	25

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Hylotrupes bajulus	0	0	100	28	22
Hylotrupes bajulus E	0	0	100	35	16
Hylotrupes bajulus L	0	0	100	35	16
Hylotrupes bajulus L (LD100)	1.1	0	98.9	21	35
Lasioderma serricorne (15 bar – 40 bar)	0	100	0		15-45
Lasioderma serricorne E (25 bar)	0	100	0	80 min	25
Lasioderma serricorne E (30 bar)	0	100	0	52 min	25
Lasioderma serricorne E (30 bar)	0	100	0	70 min	15
Lasioderma serricorne E (35 bar)	0	100	0	36 min	25
Lasioderma serricorne E (35 bar)	0	100	0	48 min	15
Lasioderma serricorne E (40 bar)	0	100	0	20 min	25
Lasioderma serricorne E (40 bar)	0	100	0	32 min	15
Lasioderma serricorne I	0	100	0	3.7	25
Lasioderma serricorne I (10 bar)	0	100	0	477.8min	25
Lasioderma serricorne I (10 bar)	0	100	0	85 min	35
Lasioderma serricorne I (10 bar)	0	100	0	478 min	25
Lasioderma serricorne I (15 bar)	0	100	0	28 min	35
Lasioderma serricorne I (15 bar)	0	100	0	50 min	25
Lasioderma serricorne I (15 bar)	0	100	0	130 min	15
Lasioderma serricorne I (15 bar)	0	100	0	80 min	35
Lasioderma serricorne I (15 bar)	0	100	0	49 min	25
Lasioderma serricorne I (15 bar)	0	100	0	170 min	15
Lasioderma serricorne I (20 bar)	0	100	0	4.5 min	35
Lasioderma serricorne I (20 bar)	0	100	0	25 min	25
Lasioderma serricorne I (20 bar)	0	100	0	40 min	15
Lasioderma serricorne I (20 bar)	0	100	0	0.2 min	25
Lasioderma serricorne I (20 bar)	0	100	0	4 min	15
Lasioderma serricorne I (20 bar)	0	100	0	24.9min	25
Lasioderma serricorne I (20 bar)	0	100	0	38.9 min	15
Lasioderma serricorne I (20 bar)	0	100	0	24.9 min	25
Lasioderma serricorne I (20 bar)	0	100	0	35 min	35
Lasioderma serricorne I (20 bar)	0	100	0	10 min	35
Lasioderma serricorne I (20 bar)	0	100	0	25 min	25
Lasioderma serricorne I (20 bar)	0	100	0	40 min	15
Lasioderma serricorne I (25 bar)	0	100	0	8 min	35
Lasioderma serricorne I (25 bar)	0	100	0	4.6 min	25
Lasioderma serricorne I (25 bar)	0	100	0	30 min	15
Lasioderma serricorne I (30 bar)	0	100	0	1.1min	35
Lasioderma serricorne I (30 bar)	0	100	0	2.5 min	25
Lasioderma serricorne I (30 bar)	0	100	0	10 min	15
Lasioderma serricorne I (30 bar)	0	100	0	4 min	35
Lasioderma serricorne I (30 bar)	0	100	0	2.5 min	25
Lasioderma serricorne I (30 bar)	0	100	0	10 min	15
Lasioderma serricorne I (35 bar)	0	100	0	1.3 min	25
Lasioderma serricorne I (35 bar)	0	100	0	6 min	15
Lasioderma serricorne I (40 bar)	0	100	0	0.3 min	25
Lasioderma serricorne L (15 bar)	0	100	0	61 min	25

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Lasioderma serricorne L (20 bar)	0	100	0	20 min	35
Lasioderma serricorne L (20 bar)	0	100	0	95min	25
Lasioderma serricorne L (20 bar)	0	100	0	120 min	15
Lasioderma serricorne L (20 bar)	0	100	0	114 min	25
Lasioderma serricorne L (25 bar)	0	100	0	31 min	25
Lasioderma serricorne L (30 bar)	0	100	0	4 min	35
Lasioderma serricorne L (30 bar)	0	100	0	13 min	25
Lasioderma serricorne L (30 bar)	0	100	0	65 min	15
Lasioderma serricorne L (30 bar)	0	100	0	2.5 min	25
Lasioderma serricorne L (30 bar)	0	100	0	14 min	25
Lasioderma serricorne L (35 bar)	0	100	0	6 min	25
Lasioderma serricorne L (40 bar)	0	100	0	3 min	15
Lasioderma serricorne L (40 bar)	0	100	0	0.3 min	25
Lasioderma serricorne L (40 bar)	0	100	0	2.7 min	25
Lasioderma serricorne P (25 bar)	0	100	0	30 min	25
Lyctus brunneus	0	0	100	21	35
Lyctus brunneus Brut 10W. internal	0	0	100	16.8	25
Lyctus brunneus Brut 10W. internal	0	4	96	10.4	25
Lyctus brunneus Brut 13W. internal	0	0	100	18.4	25
Lyctus brunneus Brut 13W. internal	0	4	96	14.8	25
Lyctus brunneus Brut 1W. internal	0	0	100	13.3	25
Lyctus brunneus Brut 1W. internal	0	4	96	8.08	25
Lyctus brunneus Brut 4W. internal	0	0	100	13.1	25
Lyctus brunneus Brut 4W. internal	0	4	96	8.11	25
Lyctus brunneus Brut 7W. internal	0	0	100	16.55	25
Lyctus brunneus Brut 7W. internal	0	4	96	15.7	25
Lyctus brunneus I external	0	0	100	7.2	20
Lyctus brunneus I external	0	0	100	1.73	25
Lyctus brunneus I external	0	0	100	1.43	28
Lyctus brunneus I external	0	4	96	4.05	25
Lyctus brunneus I außen	0	10	96	2.77	25
Lyctus brunneus L external	0	0	100	22	20
Lyctus brunneus L external	0	0	100	14.7	25
Lyctus brunneus L external	0	0	100	11.86	28
Lyctus brunneus L external	0	4	96	7.4	25
Lyctus brunneus L external	0	10	90	13	25
Oryzaephilus mercator I	16	40	44	1.4	30
Oryzaephilus mercator I	8	60	32	1.0	30
Oryzaephilus mercator I	2	0	98	1.1	30
Oryzaephilus surinamensis	2	0	98	4	15
Oryzaephilus surinamensis	2	18	80	5	15
Oryzaephilus surinamensis	2	90	8	3	15
Oryzaephilus surinamensis	2	0	98	4	20
Oryzaephilus surinamensis	2	18	80	3	20
Oryzaephilus surinamensis	2	90	8	2	20
Oryzaephilus surinamensis I	16	40	44	5.9	30
Oryzaephilus surinamensis I	8	60	32	2.9	30

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Oryzaephilus surinamensis I	2	0	98	2.63	30
Plodia interpunctella	2	0	98	4.5	15
Plodia interpunctella	2	18	80	5	15
Plodia interpunctella	2	90	8	8	15
Plodia interpunctella	2	0	98	2.5	20
Plodia interpunctella	2	18	80	3.5	20
Plodia interpunctella	2	90	8	3	20
Plodia interpunctella E (15 bar)	0	100	0	40	25
Plodia interpunctella E (20 bar)	0	100	0	10 min	25
Plodia interpunctella E (20 bar)	0	100	0	30 min	25
Prostephanus truncatus	5	75	20	2.04	20
Prostephanus truncatus	10	50	40	3.5	20
Prostephanus truncatus	15	25	60	6	20
Prostephanus truncatus	5	75	20	1.25	30
Prostephanus truncatus	10	50	40	2.75	30
Prostephanus truncatus	15	25	60	3.5	30
Prostephanus truncatus	15	25	60	6.3	20
Prostephanus truncatus	10	50	50	3.1	20
Prostephanus truncatus	5	75	20	2.2	20
Prostephanus truncatus	10	50	50	2.7	20
Prostephanus truncatus	15	25	60	3.5	30
Prostephanus truncatus	10	50	50	2.8	30
Prostephanus truncatus	10	50	50	1.8	30
Reticulitermes santonensis	0	0	100	28	22
Rhyzopertha dominica	5	75	20	1.75	20
Rhyzopertha dominica	10	50	40	2.5	20
Rhyzopertha dominica	15	25	60	5	20
Rhyzopertha dominica	5	75	20	0.92	30
Rhyzopertha dominica	10	50	40	2.5	30
Rhyzopertha dominica	15	25	60	3.5	30
Rhyzopertha dominica	15	25	60	4.7	20
Rhyzopertha dominica	5	75	20	1.9	20
Rhyzopertha dominica	15	25	60	3.3	30
Sitophilus granarius	2	0	98	21	15
Sitophilus granarius	1	0	99	10.8	15
Sitophilus granarius	1	19	80	13.4	15
Sitophilus granarius	1	95	4	8	15
Sitophilus granarius	2	0	98	13.1	15
Sitophilus granarius	2	18	80	7.3	15
Sitophilus granarius	2	90	8	6.7	15
Sitophilus granarius	3	0	97	6.9	15
Sitophilus granarius	3	17	80	5.1	15
Sitophilus granarius	3	12	85	3.9	15
Sitophilus granarius	4	0	96	21.9	15
Sitophilus granarius	4	16	80	8.4	15
Sitophilus granarius	4	80	16	6.2	15
Sitophilus granarius	1	0	99	13	20

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Sitophilus granarius	1	19	80	5.8	20
Sitophilus granarius	1	95	4	4.7	20
Sitophilus granarius	2	0	98	7.4	20
Sitophilus granarius	2	18	80	9.8	20
Sitophilus granarius	2	90	8	2.9	20
Sitophilus granarius	3	0	97	5.3	20
Sitophilus granarius	3	17	80	2.8	20
Sitophilus granarius	3	12	85	2.3	20
Sitophilus granarius	4	0	96	6.4	20
Sitophilus granarius	4	16	80	5.7	20
Sitophilus granarius	4	80	16	2.2	20
Sitophilus granarius aL	1	0	99	37	20
Sitophilus granarius all stages	0	100		0.02	40 bar
Sitophilus granarius all stages	0	100		0.04	30 bar
Sitophilus granarius all stages	0	100		0.08	20 bar
Sitophilus granarius all stages	0	100		0.33	10 bar
Sitophilus granarius all stages	0	100	0	1	40
Sitophilus granarius all stages	0	100	0	3	35
Sitophilus granarius all stages	0	100	0	7	30
Sitophilus granarius all stages	0	100	0	14	25
Sitophilus granarius all stages	0	100	0	25	20
Sitophilus granarius all stages	0	100	0	42	15
Sitophilus granarius brood, stadium 4	1	0	99	40	15
Sitophilus granarius brood, stadium 4	1	19	80	60	15
Sitophilus granarius brood, stadium 4	1	95	4	22	15
Sitophilus granarius brood, stadium 4	2	0	98	60	15
Sitophilus granarius brood, stadium 4	2	18	80	53	15
Sitophilus granarius brood, stadium 4	2	90	8	15	15
Sitophilus granarius brood, stadium 4	3	0	97	65	15
Sitophilus granarius brood, stadium 4	3	17	80	50	15
Sitophilus granarius brood, stadium 4	3	12	85	24	15
Sitophilus granarius brood, stadium 4	4	0	96	60	15
Sitophilus granarius brood, stadium 4	4	16	80	48	15
Sitophilus granarius brood, stadium 4	4	80	16	39	15
Sitophilus granarius brood, stadium 4	1	0	99	30	20
Sitophilus granarius brood, stadium 4	1	19	80	30	20
Sitophilus granarius brood, stadium 4	1	90	8	20	20
Sitophilus granarius brood, stadium 4	2	0	98	31	20
Sitophilus granarius brood, stadium 4	2	18	80	25	20
Sitophilus granarius brood, stadium 4	2	95	4	7	20
Sitophilus granarius brood, stadium 4	3	0	97	35	20
Sitophilus granarius brood, stadium 4	3	17	80	42	20
Sitophilus granarius brood, stadium 4	3	12	85	15	20
Sitophilus granarius brood, stadium 4	4	0	96	40	20
Sitophilus granarius brood, stadium 4	4	16	80	31	20
Sitophilus granarius brood, stadium 4	4	80	16	40	20
Sitophilus granarius brood, stadium 5	1	0	99	45	15

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve); jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Sitophilus granarius brood, stadium 5	1	19	80	39	15
Sitophilus granarius brood, stadium 5	1	95	4	35	15
Sitophilus granarius brood, stadium 5	2	0	98	52	15
Sitophilus granarius brood, stadium 5	2	18	80	49	15
Sitophilus granarius brood, stadium 5	2	90	8	27	15
Sitophilus granarius brood, stadium 5	3	0	97	53	15
Sitophilus granarius brood, stadium 5	3	17	80	41	15
Sitophilus granarius brood, stadium 5	3	12	85	34	15
Sitophilus granarius brood, stadium 5	4	0	96	55	15
Sitophilus granarius brood, stadium 5	4	16	80	49	15
Sitophilus granarius brood, stadium 5	4	80	16	40	15
Sitophilus granarius brood, stadium 5	1	0	99	30	20
Sitophilus granarius brood, stadium 5	1	19	80	32	20
Sitophilus granarius brood, stadium 5	1	95	4	24	20
Sitophilus granarius brood, stadium 5	2	0	98	25	20
Sitophilus granarius brood, stadium 5	2	18	80	21	20
Sitophilus granarius brood, stadium 5	2	90	8	19	20
Sitophilus granarius brood, stadium 5	3	0	97	30	20
Sitophilus granarius brood, stadium 5	3	17	80	45	20
Sitophilus granarius brood, stadium 5	3	12	85	26	20
Sitophilus granarius brood, stadium 5	4	0	96	40	20
Sitophilus granarius brood, stadium 5	4	16	80	32	20
Sitophilus granarius brood, stadium 5	4	80	16	38	20
Sitophilus granarius E	1	0	99	10	20
Sitophilus granarius I	1	0	99	10	20
Sitophilus granarius jL	1	0	99	10	20
Sitophilus granarius mL	1	0	99	21	20
Sitophilus granarius P	1	0	99	42	20
Sitophilus oryzae	16	20	64		28
Sitophilus oryzae	10	50	40	0.85	28
Sitophilus oryzae	4.4	78	17.6	0.49	28
Sitotroga cerealella E	16	20	94	7.1	15
Sitotroga cerealella E	12	40	48	7.0	15
Sitotroga cerealella E	8	60	32	5.2	15
Sitotroga cerealella E	2	90	8	4.8	15
Sitotroga cerealella E	16	20	94	4.8	25
Sitotroga cerealella E	12	40	48	2.8	25
Sitotroga cerealella E	8	60	32	2.1	25
Sitotroga cerealella E	2	90	8	1.9	25
Tineola bisselliella	0	100	0	28	22
Tineola bisselliella E	2	0	98	7	25
Tribolium castaeum	16	20	64		28
Tribolium castaeum	10	50	40	2.46	28
Tribolium castaeum	4.4	78	17.6	0.96	28
Tribolium castaneum I	16	40	44	6.2	30
Tribolium castaneum I	8	60	32	4.5	30
Tribolium castaneum I	2	0	98	3.7	30

Insect species and developmental stages ***The values beyond 5 days have been determined with regression and program TableCurve);** **jL, L1 young larvae; L3 medium age larvae; aL old larvae; I adults; In: n days old adults; Ln: n days old larvae; pP: prepupae; P pupae; E eggs; L larvae; schw B: weak infestation (1-2 larvae per bean); st B: strong infestation (10-12 larvae per bean)**	**O2 vol%**	**CO2 vol%**	**N2 vol %**	**LD95 days**	**temperature °C**
Tribolium confusum	2	0	98	4.5	15
Tribolium confusum	2	18	80	5	15
Tribolium confusum	2	90	8	5	15
Tribolium confusum	2	0	98	4	20
Tribolium confusum	2	18	80	3	20
Tribolium confusum	2	90	8	2	20
Tribolium confusum I	16	40	44	5.4	30
Tribolium confusum I	8	60	32	4.2	30
Tribolium confusum I	2	0	98	3.7	30
Trogoderma angustum L	0	0	100	6.6	25
Trogoderma angustum L	0	4	96	3.6	25
Trogoderma angustum L	0	10	96	2.9	25
Trogoderma grasmani I	16	40	44	2.2	30
Trogoderma grasmani I	8	60	32	1.4	30
Trogoderma grasmani I	2	0	98	1.8	30
Trogoderma inclusum I	16	40	44	4.5	30
Trogoderma inclusum I	8	60	32	4.0	30
Trogoderma inclusum I	2	0	98	2,8	30

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