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# Phytoparasitic nematode management post-methyl bromide: Where to for Zimbabwe?

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Methyl bromide, a broad spectrum fumigant that has been in use for over 70 years, would be phased out even in developing countries in 2015. The chemical is mainly used as a pre-plant soil sterilant and disinfectant in warehouses, ships and aeroplanes. Methyl bromide is being phased out because it is an ozone depletor. This calls for alternative chemicals and non-chemical methods to be developed to replace methyl bromide. A number of alternative chemicals, including chloropicrin, 1,3-dichloropropene, methyl isothiocynate, methyl iodide and sodium azide have been tried in the developed world as replacements. Of these, methyl iodide is the most promising because it has the same efficacy as methyl bromide, and is not ozone-depleting. The other alternatives like 1,3-dichloropropene and chloropicrin have limited pest spectrum of activity and have to be applied in combination with each other or with herbicides. Non-chemical methods like crop rotation, resistant cultivar use, organic matter addition and solarization have been accepted by farmers. Biofumigation is a relatively new technique in Zimbabwe and is under experimental evaluation. Biotechnology has been adopted for use in pest management in Zimbabwe where the Tobacco Research Board spearheads the national tobacco programme of producing varities resistant to root knot nematodes. The Scientific and Industrial Research and Development Centre is mandated with producing both food and cash crops that are resistant to pests. Whereas tobacco seedling production was heavily reliant on methyl bromide, the Tocacco Research Board has introduced the float tray system whose adoption by small-scale farmers is at between 30 and 40%. Fambidzanayi Permaculture Centre is also encouraging farmers to organically produce both horticultural and nonhorticultural crops. The management of nematodes and other pests post methyl bromide will rely on integrating the different methods i.e. both chemical and non-chemical methods.

**Key Words:** nematodes, methyl bromide, nematode management, phase-out.

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## Introduction

### *Production, Properties and Uses of Methyl Bromide*

Methyl bromide (MBr) has been in use for over 70 years. Prior to 1999, about 70 000 tonnes of this chemical were produced annually, with the USA being the main producer and consumer. The UK, Australia, France and Japan, India and China also produce, consume and export MBr.

MBr is a volatile broad spectrum biocide with fumigant properties. It is a colourless and odorless gas at normal temperature and pressure. It is readily soluble in lower alcohols, ethers, esters, ketones, halogenated hydrocarbons, aromatic hydrocarbons and carbon disulphide (www.epa.org). It is fast-acting, requiring only a short time between application and planting. MBr causes severe harmful effects to the eyes, lungs and skin. No known cases of resistance have been reported with MBr.

Between 70-80% of MBr is used for soil sterilization pre-planting. MBr soil fumigation has traditionally been practiced in high-input, high-value production systems (Ristaino and Thomas, 1997). The chemical has been used to effectively control root knot nematodes (*Meloidogyne* spp) and *Cyperus* spp which are problematic in tropical and subtropical climates (Gilreath and Santos, 2008). In the USA, MBr is used to disinfect grains and horticultural produce after harvesting. The chemical is also used to treat plant material to prevent the spread of regulated pests. Food production premises are also disinfected with MBr to remove deep-rooted pests in cracks and crevices of the building. Ships and aircraft are also fumigated to eradicate deep-seated infestations of rodents and insects (www.ers.usda.gov). In Zimbabwe, the bulk of MBr is used to sterilize soils in tobacco and horticultural nurseries. Another significant quantity is used in grain fumigation.

### *The Methyl Bromide Phase-Out Programme*

MBr was identified as ozone depleting in 1985 (Ristaino and Thomas, 1997; Rosskopf *et al.*, 2005). Ozone depletion causes increased ultraviolet radiation to reach the earth's surface, with potential effects to human health, the environment and agricultural crops. In 1992, MBr was added to the list of ozone depletors under the Montreal Protocol. By September 1997, controls on MBr production and use had been agreed to under the Montreal Protocol. There was to be 50% cut in production by 2001, a 70% reduction by 2003 and total phasing out by 1 January 2005 in developed countries. Developing nations were to freeze consumption in 2002 at a 1995-98 average, reduce consumption from that baseline by 20% in 2005, and are to phase out MBr by 2015 (USDA Economic Services Research, 2000).

However, MBr is still being produced in the developed world (Zasada *et al.*, 2010). This is because the Montreal Protocol allows for critical uses exemptions to the ban after the phase-out dates. Critical use exemptions are based on determining that a technically and economically feasible alternative with acceptable health and environmental effects is not available and that withdrawal of MBr would result in a significant market disruption of selected commodities (UNEP, 2000). In the USA, MBr is still being used in horticulture, quarantine and pre-shipment (Brennen, 2008).

The broad spectrum of activity of MBr had made it the primary means for the control of soilborne pests in most cropping systems. This led to dearth in the development of integrated control strategies for the management of soilborne pests (Martin, 2003). However, a number of alternatives have been proposed and recommended for use to replace MBr. This article will look at these alternatives and attempt to qualify their applicability to Zimbabwe, for nematode management.

## Chemical alternatives to methyl bromide

### *Chloropicrin*

Chloropicrin is a toxic liquid that is applied by injection into the soil and sealed with a polythene sheet. The minimum period from treatment to planting is at least six weeks. Chloropicrin has good fungicidal activity, but high doses are required for effective nematode and weed control (O'Neill, 1988; Duniway, 2002). Chloropicrin is commonly applied in combination with other fungicides like metham sodium, iodomethane and 1,3-dichloropropene for improved nematicidal and herbicidal properties (Duniway, 2002). An emulsifiable concentrate formulation of chloropicrin is available for application through drip irrigation. Chloropicrin has short stability in the soil, with microbial degradation primarily responsible for its inactivation (Gan *et al.*, 2000).

### *Dichloropropene*

Dichloropropene (1,3-dichloropropene) is a colourless liquid with a sweetish odour. This chemical causes gastrointestinal, skin, eye and respiratory tract irritation in humans. The chemical is also carcinogenic. 1,3-dichloropropene (1,3-D) is injected into the soil, primarily to control nematodes. It has little effect on fungi, weeds and insects (Gilreath *et al.*, 2006). It is a relatively cheap soil disinfectant. In the USA, 1,3-D is marketed as a stand-alone fumigant, or in combination with chloropicrin, metolachlor and trifluralin (Noling, 2000).

### *Methyl iodide*

This broad-spectrum chemical is mobile in the soil and functions effectively as a fumigant. It's spectrum of activity is similar to MBr. It is not an ozone depletor because it is rapidly broken down by ultraviolet light. Methyl iodide (iodomethane) can be applied using the same equipment as MBr. It has longer persistence than MBr, and is usually combined with chloropicrin (Gan *et al.*, 2000). In the USA, it is registered for use on tomatoes, peppers, fruit and nut trees, ornamental plants and vines.

### *Metham Sodium and Dazomet*

Both metham sodium and dazomet degrade to form the fumigant methyl isothiocyanate when applied to the soil. Metham sodium is a liquid formulation while dazomet is granular formulation of this fumigant. Metham sodium is broad spectrum and particularly effective against nematodes and weeds. It has poor soil mobility, with movement limited to a diameter of 7.5-10 centimetres from the point of application (Martin, 2003). If metham sodium is injected following 1,3-D and chloropicrin, it reduces the population of *Cyperus* in tomatoes, without sacrificing nematode control (Gilreath *et al.*, 2006; Vaculin and Gilreath, 2006).

Dazomet has good activity against fungi, nematodes, weeds and weed seeds, including *Striga* spp. For effective treatment with dazomet, soil temperature must be above $7^0$C, and soil moisture must not be below 50% field capacity and not oversaturated. The soil must be sealed with plastic for at least 14 days in warm soils or 28 days in cooler soils to retain the fumigant. Allow residual gas to disperse over a period of 14-28 days before planting a crop (O'Neill, 1988). High concentrations of methyl isothiocyanate do not readily dissipate, and end up causing phytotoxicity problems. Thus, uniform watering is needed to activate the entire product in the soil prior to planting a crop. Dazomet has strong herbicidal action, and is often paired with other fumigants to broaden the spectrum of pest control (Haar *et al.*, 2003).

### *Formaldehyde*

Commercial formaldehyde is produced and sold as an aqueous solution with a pungent and suffocating smell. It has broad-spectrum activity against bacteria and fungi, but has limited effect on weeds, and no activity on insects. It is toxic to earthworms, man and plants. Prior to the availability of volatile chemical fumigants, formaldehyde used to be one of the most used soil disinfectants. A pre-planting waiting period of 4-10 weeks should be observed, depending on soil temperature, soil type and treatment depth (O'Neill, 1988).

### *Sodium azide*

Aqueous solutions of sodium azide are stable above pH 9, but convert to the biocide hydrazoic acid below pH 8 (Martin, 2003). It controls soilborne pathogens, nematodes and weeds. It has been used in tomato, pepper and cotton trials. For field applications, the product must be mixed with a stabilizer that is above pH 9 and injected into irrigation pipes just before distribution to the drip tapes. There has been poor field control of *Meloidogyne* and *Tylenchulus semipenetrans* (Schneider *et al*., 2002).

### *Dimethyl Disulphide*

Dimethyl disulphide is a ubiquitous natural product common in the global sulphur cycle and is detected as a metabolite in numerous biological processes (Ntow and Ajwa, 2009). This chemical can be used alone, or in combination with chloropicrin. It has been reported to be effective against *Meloidogyne* spp (Church *et al*., 2004). It is not yet registered in the USA (Zasada *et al*., 2010).

### *Oxamyl and fosthiazate*

Both oxamyl and fosthiazate are non-fumigant nematicides. In the USA, oxamyl is registered for use on tomato, eggplant, cucurbits, pepper and tree fruit crops. In Zimbabwe, oxamyl is marketed at Vydate, and is used as a broad spectrum insecticide of field and vegetable crops. Oxamyl may be applied directly onto plants or on the soil surface. In the USA, fosthiazate is currently registered for use on tomatoes only. Fosthiazate can be applied through drip irrigation pipes, thereby reducing the risk of human exposure (Leyes, 2006). Both oxamyl and fosthiazate could be useful for supplemental nematode control or where post-plant applications are needed to enhance fumigant performance or where nematode pressure is low (Burelle, 2005).

## Non-chemical alternatives

### *Cultural Control*

Cultural control covers a wide range of activities that are designed to interfere with nematodes' survival and reproduction. The activities can be readily employed by small scale and even subsistence farmers for pest management. Many such methods are sustainable in the long run. Below are some such activities that can be implemented for nematode management:

### *Crop Rotation*

This is the practice of growing different crops on the same piece of land in sequence. Crop rotation is widely adopted, and has been practiced since ancient times (De la Vega, 2006). The basic principle of crop rotation for nematode management is reduction of initial inocula of damaging nematode species to levels that allow following crop(s) to establish and complete early growth before heavy pest attack. Sufficient time should lapse after growing a susceptible host crop so that the nematode population declines to a level that allows the next susceptible crop to grow and yield at an acceptable rate (Rodriguez-Kabana and Canullo, 1992). This is achieved by alternating a poor host, tolerant or resistant crop with susceptible host crops. Allow the longest time interval between growing susceptible crops to maximize yield.

Fallows, allelopathic plants, trap crops or green manure crops may be included in a rotation (Halbrendt and LaMondia, 2004). A good rotation should not include a crop susceptible to the main nematode pest more than once in four growing seasons. Rotations are difficult to implement where, the economic returns for lesser-valued rotational crops cannot be justified. They are more applied to annual than in perennial cropping systems. Sometimes, rotations are non-sustainable as they impose non-optimal use of land and can increase total acreage involved in cropping (Atkinson *et al*., 2003).

### *Resistant Cultivars*

A resistant cultivar is one that is immune to nematode attack. Resistant cultivar use can be the most useful and cheapest means of nematode control for farmers. Most of the plant resistance genes are effective against sedentary endoparasitic nematodes like *Meloidogyne*, *Globodera*, and *Hirschmaniella*. Resistance to feeding by ectoparasitic nematodes like *Xiphinema*, *Trichodorus*, *Longidorus*, and *Hoplalaimus* or migratory endoparasitic nematodes like *Pratylenchus* and *Ditylenchus* has been more difficult to identify and is often expressed as reduced reproduction in comparison to a susceptible cultivar (Dale and Potter, 1998; Barker, 2003). Most of the resistance genes against sedentary endoparasitic nematodes prevent or greatly reduce nematode population increases in roots. Resistance is characterized by failure or death of specialized feeding cells in the host (Williamson and Kumar, 2006).

Plant resistance to nematodes has been identified in a number of crops. Cultivars resistant to different species and isolates of the root knot nematodes have been selected for in beans, peas, soyabeans, pepper, sweet potato and cowpea (Roberts, 1992). The *Mi-1* gene for resistance to *Meloidogyne incognita*, *M arenaria* and *M. javanica* in tomato has been used successfully for more than 125 years (Williamson, 1998). Resistance to *Globodera* in potato is conferred by the dominant, major effect *H1* gene (Castelli *et al*., 2005).

However, resistance tends to break down due to high temperature. Cultivars may not be acceptable because of susceptibility to other pests and diseases, unacceptably high input requirements, poor quality or poor marketability. One approach commonly used in fruit and nut trees to circumvent the above problems is to graft horticulturally desirable scions onto rootstocks that have resistance to specific diseases. This approach has been used in the Mediterranean region and Japan with tomato and cucurbit production to enhance yield and manage soilborne diseases (Zasada *et al*., 2010). A major limitation with this approach is the added plant cost associated with plant grafting. This would make it less appealing to smallholder farmers in Zimbabwe.

### *Fallowing*

Fallows come in different forms i.e. clean/bare fallow and grass fallows. Clean fallows are best for reducing nematode populations. When the ground is left bare, nematodes are exposed to high temperatures and so desiccate. Also during the fallow period, nematodes have no food and so starve to death. However, bare fallowing exposes the soil to erosion.

Grass fallows can be achieved by planting of grass or removal of weeds other than the native grasses in a bush fallow. Common grasses for rook knot nematodes are *Eragrostis curvula*, *Chloris gayana*, *Panicum maximum*, and *Cynodon dactylon*. There is need to continuously pull out broad-leaf weeds like *Oxalis latifolia*, *Bidens pilosa* and *Amaranthus* spp in a grass fallow because many of them are good root knot nematode hosts (Godfrey-Sam-Aggrey and Tekie, 1990). *Echinochloa colona*, *Eleusine indica* and *Solunum nigrum* host the banana nematode during fallow periods, and must be pulled out (Chabrier and Quénéhervé, 2008).

### *Escape Cropping*

This is the practice of growing crops at times that are not favourable for nematodes, for example when temperature is too high or too low for nematode infection or development, or when nematodes populations are at low thresholds. In Zimbabwe, growing crops in winter (when temperature falls below $15^0$C) helps the crop escape nematode attack.

### *Antagonistic Plants and Trap crops*

Antagonistic plants produce chemicals in their roots that are toxic and/or repellant to plant parasitic nematodes. Examples of such plants include *Tagetes* spp, *Datura stramonium* and *Ricinus communis*. Roots of asparagus produce asparaguric acid glycoside that is toxic to most plant parasitic nematodes. Roots of *Tagetes*, *Datura stramonium* and *Ricinus communis* induce premature nematode egg hatching, block mitosis and meiosis, and reduce galling intensity of roots of susceptible plants. This is due to the alkaloids terthienyl, hyosine and ricinine present, respectively. Root diffusates of crucifers reduce the pathogenicity of nematodes on potato. A compound in citrus roots is toxic to *Tylenchulus semipenetrans*. The herb *Sphenoclea zeylanica* produces exudates that kill 99% of rice root nematodes (*Hirschmanniella oryzae*) in field soil (Mohandas et al., 1981). Antagonistic plants can be grown in rotation and intercropping, and have been recommended for nematode control in Zimbabwe.

In trap cropping, a susceptible crop is grown on a land heavily infested with nematodes. The trap crop allows invasion but only partial nematode development in roots. Plants are uprooted and destroyed before the crop reaches maturity. *Sesbania rostrata*, a legume that can be grown as a green manure crop, reduces the population of *H oryzae* by acting as a trap crop (Prot *et al*., 1992). However, *Sesbania* is highly susceptible to *Meloidogyne graminicola* that occurs commonly with *Hirschmaniella spp*. Cowpea can be grown as a trap crop to *Meloidogyne* spp.

Smallholder farmers rarely use green manure crops because they do not get direct benefits from them. If *Tagetes minuta* is grown as an intercrop, its detrimental effects outweigh the benefits of nematode control. Trap crops can be grown most effectively as cover crops in sequential rotations.

### *Organic Soil Amendments*

The addition of organic remains to the soil is an established ancient agricultural practice known to farmers. Poultry manure, cow dung, green manure and crop residues have been widely accepted among smallholder farmers (Agbenin, 2011). Cow dung and poultry manure reduce the population of root knot nematodes and other plant parasitic nematodes (Poswal and Akpa, 1991). Partially decayed cassava peels are effective against *Pratylenchus brachyurus* [39]. Zimbabwean smallholder farmers in Chinamhora District have controlled root knot nematodes on vegetables by adding organic manure (Page, 1997).

Organic matter improves both the nutrient and water holding capacities of the soil. This improves plant growth vigor and hence increases tolerance to nematodes. High soil organic matter also stimulates microbial activity and increases the presence of microbes antagonistic to nematodes. Decomposition of organic residues releases compounds that may be nematicidal. The main disadvantage of this method is the large quantities of organic remains required.

### *Improved Crop Husbandry and Field Hygiene*

Farmers growing bananas commonly prop their crops to reduce damage caused by the *Radopholus similis*. A properly watered and fertilized crop is far much able to withstand nematode attack than a poorly-watered and improperly fertilized crop. Such a crop tends to increase root growth and so compensate for damage by nematodes. During the growing season, plants that are heavily infected by nematodes should be uprooted and burnt. Field cleaning can also be done prior to planting. In Martinique (French West Indies), banana field clean-up of lands is followed by either a fallow period, or an appropriate rotation and then nematode-free *in vitro* plants (Chabrier and Queneherve, 2008). Clean water from boreholes, municipalities or other protected sources can be used when raising seedlings and other high-value crops. Farm implements and machinery should be cleaned before moving from one field to another.

### *Biofumigation*

This is the practice of incorporating brassicaceous plant material into the soil to control soilborne pathogens and pests. When brassicas are mechanically chopped and quickly incorporated into the soil, they release isothiocyanates in sufficient quantities to kill plant parasitic nematodes (Halbrendt, 1996; Ploeg, 2008). Biofumigation has been practiced for high-value crop production systems with variable results achieved (Lazzeri *et al*., 2003; Sterling and Sterling, 2003, Lawrence and Matthienssen, 2004). This has been principally because the brassica cultivars and species used have varied concentrations of glucosinolates in their tissues (Sang *et al*., 1984; Craig *et al*., 2005). Efficacy is also affected by the stage of plant development, method of tissue maceration, method and speed of incorporation of tissues in the soil, soil temperature, soil moisture and soil type (Matthienssen *et al*., 2004). Different nematode genera have different tolerances to isothiocyanates (Zasada and Ferris, 2003).

Biofumigation adds organic matter to the soil. It can replace synthetic chemicals which tend to cause groundwater pollution. *Brassica* residues have also been shown to suppress common scab (*Streptomyces scabies*) of potato (Gouws and Mienie, 2000). It has also been reported that biofumigation has the same effect at MBr against *Meloidogyne incognita* on pepper and Take-all disease of wheat (Bello *et al*., 2001; Kirkegaard, 2004). Biofumigation trials are being run in Zimbabwe, with the Department of Agricultural Science at Bindura University of Science Education among the pioneers.

## Physical Control

This tactic relies on the use of physical factors like temperature, water and heat to control nematodes.

### *Use of Heat*

#### *Heat Treatment of Plant Material*

Bulbs, corms, roots and tubers may be hot-water treated to kill nematodes. The temperature and time required to kill nematodes vary with the nematode species, plant type and even plant varieties. Suitable and efficient equipment is needed if good control results are to be obtained. The plant material should be completely immersed in a large volume of water. Temperature must be accurately controlled so that the plants are not killed. Stubble burning is useful in destroying foliar pathogens. Infected plants are uprooted, dried and burnt to kill soil nematodes.

#### *Heat Treatment of Soil*

Small soil quantities may be placed in a tin and heated to $80^0$C to kill nematodes. The heat may be supplied from an electrical source, or charcoal. Turning the soil prior to or during a hot season exposes nematodes to heat and hence they desiccate.

Solarization is a form of soil pasteurization whereby the sun’s energy is trapped beneath plastic sheets spread over a soil surface. It was first described in 1976 as a pre-plant soil treatment for controlling soilborne pathogens and weeds (Katan *et al*., 1976). It is a cheap and cost-effective means of soil treatment that is compatible with other pest management practices (Chellemi *et al*., 1997). For pathogens to be killed, the soil should be exposed to high solar radiation for at least 30 days. The depth of heat penetration and efficacy of solarization are improved by ploughing before covering the soil with either black or clear plastic. In Zimbabwe, solarization can best be done from late September to the period before the onset of the rainy season when daily maximum temperature reach above $35^0$C throughout the country. Solarization will best deal with plant parasitic nematodes that are not deeply distributed in the soil (Stapleton and DeVay, 1983). It can be combined with other pest management techniques like application of 1,3-D to improve nematode suppression (Schneider *et al*., 2003). Organic amendments can be added to solarized soils thereby potentially increasing the nematicidal activity of the amendments.

### *Soil Steaming*

If the soil is heated to $70^0$C, most plant pathogens are killed without leaving a biological vacuum. However, some viruses like tobacco mosaic virus and cucumber green mottle mosaic virus are not inactivated even at $100^0$C. Steaming can be done to kill the viruses. Steaming is expensive, relatively slow and labour intensive. Only a small area can be treated at a given time. However, there is no waiting period before planting a crop and the method is environmentally safe.

### *Flooding*

This is the process of inundating a piece of land with water for a period of time. Flooding can be done either naturally or artificially. Flooding is effective against soil nematodes. Artificial flooding is not appropriate for small scale farmers. Large volumes of water are required where flooding is practiced. The soil should have good water holding capacity. The land should be fairly flat so that water does not run off quickly. Some pathogens are not killed by flooding. In Zimbabwe, there are some vleis (natural wetlands) that smallholder farmers use mainly for market gardening.

## Biological control

This is the use of living organisms like bacteria, fungi and other nematodes to control nematode pathogens. Several species of nematophagous fungi prey on nematodes. The fungi produce adhesive mycelia hyphal branches that trap nematodes by adhesion. For example, the cereal cyst nematode is controlled by *Nematophthora gynophila* and *Verticillium chlamydosporium*. The fungus *Dachylella oviparasitica* parasitizes eggs of *Meloidogyne* spp.

Spores of the bacterium *Pasteuria penetrans* adhere to the cuticle of the infective *Meloidogyne* and *Pratylenchus* juveniles, germinate and penetrate the nematode body. They then consume its contents, leading to death of the infected nematode (Agrios, 2005). *Mononchus* is a general predator of phytoparasitic nematodes.

It is a known fact in Zimbabwe that the addition of organic amendments to a soil enhances the activity of microbes antagonistic to plant parasitic nematodes. However, there is need to strike a balance between adding organic remains to a crop so as to promote the proliferation of biological control agents and upsetting the nutritional requirements of certain crops. In tobacco, adding organic matter might avail excessive nitrogen to the crop at stages that do not require the nutrient, thus reducing quality.

Biological control is generally slow-acting. It takes some time to build up populations of microorganisms that will bring pest population to levels that will not cause economic damage to the crop. It does not eradicate the pathogen, hence the crop continues to suffer damage. In Zimbabwe's communal areas, it is becoming more and more difficult to get organic amendments that can be added to the soil. This is principally due to the low productivity that is now a common occurrence. In most instances, plant residues are usually harvested to feed ruminant livestock.

## Legislation

Legislation is not a distinct method of control, but represents a legal enforcement of other control methods. In Zimbabwe, the Plant Pests and Diseases Act (Chapter 128) provides for the eradication and prevention of the spread of plant pests and diseases, as well as the prevention of the introduction of plant pests and diseases into the country.

### *Import and Export Regulations*

The importation of growing media, injurious organisms, invertebrates, plants and plant products or seeds is controlled through the issuing of plant permits. Such permits, issued by authorities at the Plant Protection Institute in the Ministry of Agriculture may impose certain conditions depending on the country of origin and type of produce material. The permit may be refused on the basis of the known presence of pests and diseases in the country of origin, and which do not occur in Zimbabwe. The imported material may need to be placed in quarantine for a specified time to ensure that no pests or diseases are present before being released to the importer. Also, on the import permit, there may be certain conditions imposed. For example, the authorities of the exporting country may be asked to issue a phytosanitary certificate stating that the items have been examined by plant inspector and found free of specified pests and diseases, or that some disinfection treatment is done by the exporting country. If such conditions are not met, the imported item may be destroyed without compensation. Similar inspections and issuance of phytosanitary certificates are also carried out by the local authority for items intended for export. Plant inspectors are stationed at all ports of entry into the country (including airports and border posts). Zimbabwe's Plant Quarantine Unit is housed at the Henderson Research Station in Mazoe, some 35km north of Harare.

## Biotechnology

Biotechnology offers sustainable solutions to the problem of plant parasitic nematode control. Endeavors to genetically engineer crop resistance to nematodes have shown much promise, especially for the root knot nematode and the cyst nematodes. The major strategies being employed in bioengineering include: the transfer of natural resistance genes to susceptible crops, the disruption of biochemical signals between nematodes and plants during the parasitism process and the expression of nematode toxic proteins in plant cells (Vrain, 1999). An example where biotechnology has been used with success is in tobacco. Transgenic lines of tobacco with the nematode-responsive element of the promoter *TobRB7* gene to give antisense-*TobRB7* construct provide a moderate level of root knot nematode resistance. Transgenic plants introduced with proteinase inhibitors also provide significant control of cyst and root knot nematodes (Barker, 2003).

Zimbabwe has a policy on biotechnology adoption formulated by the Research Council of Zimbabwe. The policy prioritizes the use of biotechnological aspects in crop improvement. The Biotechnology Institute at the Scientific and Industrial Research and Development Centre (SIRDC) prioritizes the development of commercial micro-propagation systems for such crops as cassava, sweet potatoes, and Irish potato. The major constraints to crop production addressed by the Institute are drought tolerance, crop responses low fertility, pests and diseases, and weeds. Food crops like maize, sorghum and millet are given high priority together with cash crops like cotton, tobacco and vegetables. Biotechnology has been fully embraced in the national tobacco research programme of the Tobacco Research Board (TRB) where cultivars with resistance to *Meloidogyne* spp are being bred.

**Case studies**

*Float Trays: Zimbabwe's Alternative to Methyl Bromide in Tobacco Seedling Production.*

Tobacco (*Nicotiana tabacum*) is one of the most economically viable crops produced in Zimbabwe. It has been the country's major agricultural foreign currency earner since independence in 1980. In the 2010-11 season, tobacco earnings totalled US$347.8 million.

Tobacco seedling production has traditionally relied on the use of MBr for soil sterilization. However, the phase-out of MBr has called for alternative seedling production technologies to be identified, developed and implemented as part of global efforts to combat the use of ozone depletors. Zimbabwe has set herself the deadline of 2011, four years in advance of the Montreal Protocol deadline, to phase out MBr.

The TRB, with support from the United Nations Development Organization and the Government, undertook to replace MBr with Float Trays (FTs) for seedling production. From 2006, the TRB has been training farmers on the use of FTs. Over 15 000 farmers have been trained, and over 1.7 million trays and 753 638cm$^3$ of black polyethene plastic paper has been distributed to trainees. This is enough to produce seedlings for 70 000 hectares. Adoption of the FT method based on 2006-9 uptake and attendance stood at between 30 and 40%.

The FT technique relies on the use of artificial media to grow tobacco, instead of the soil. The trays used are made from expanded polystyrene, and are about 98% air. As a result, if placed in water, the trays float. They measure 670mm long by 345mm wide by 60mm deep. The number of cells per tray varies, and recommended trays have 200, 242 and 300 cells. More than 75% of seedlings raised in FTs are transplantable.

The FT method allows farmers to optimize land use. 20m$^2$ of land can produce seedlings for one hectare compared to 100m$^2$ of land under the traditional system. There is cost effective employment of integrated pest and disease management. Resource utilization is also economical given that they are applied over a smaller area. There is production of more uniform seedlings that ensure easier field management of the crop.

Small scale farmers have not embraced this technology at the levels that were anticipated. Farmers have complained that it is not easy to secure the trays and quarry to mix with seed for even seed distribution at planting. They are frustrated that trays are only available in Harare, far away from most farms. Farmers also reckon the technology is too technical. Sales records also show that most of the trays are taken up by large scale commercial farmers.

To address some of the concerns of farmers, a factory was set up at TRB in 2009 to produce the trays. Each tray costs US$2.50, and farmers are being educated on the importance of investing some of their earnings in this technology. The TRB has also established field schools so that more farmers are trained on this technology. Despite the challenges faced by smallholder farmers, the FT technology is the way to go as Zimbabwe braces for the total phase-out of MBr 2015.

### *Farming Nature's Way at Fambidzanai Permaculture Centre*

Since independence, Zimbabwean communal farmers have been persuaded to use increasing amounts of fertilizers and pesticides on both food and cash crops. As a result, pests have developed resistance and soils have become more acidic and infertile. The use of expensive and toxic inputs has brought health and financial problems to many farmers and families. To counter this trend, the Zimbabwe Institute of Permaculture (ZIP) Research, was set up to offer safe and sustainable alternatives to synthetic fertilizers and pesticides. ZIP Research operated from the Eco-Lab at Fambidzanai Permaculture Centre, 20 km west of Harare. One section of the lab is devoted towards research into indigenous natural enemies of common pests, while another section is dedicated towards training Farmer Field Workers in natural pest management and organic farming methods (Page, 1997).

At Fambidzanayi Permaculture Centre, farmers are trained via the "learning through experimentation" approach. Training is given to farmers rather than extension workers. Farmers are trained in aspects that help reduce pesticide use in their farming systems. Farmers are also made aware of environmental issues. In some instances, local extension officers are trained in natural pest management and organic farming so they can help provide follow-up support to farmers trained in natural pest management.

The Eco-lab at Fambidzanayi Permaculture Centre trains farmers in soil science, insect life cycles, pest-predator relationships, disease transmission and development and the way natural and synthetic pesticides work. This is done through a series of "in-field" and "jam-jar" experiments. Farmers are trained on scouting for pests and diseases, and control strategies. They also examine the efficacy of local natural pesticides and comparative susceptibility of crop varieties to pests. Farmers in Chinamora district, 40 km north of Harare, who have been trained at Fambidzanayi Permaculture Centre have discovered that extracts of *Datura stramonium* and rotating tomatoes, peas and carrots with cabbages and onions are effective in controlling root knot nematodes.

Fambidzanayi Permaculture Centre is also involved with farmers in the Zambezi Valley to grow cotton and other crops. Farmers are growing organic cotton as they try to reduce the heavy synthetic pesticide use associated with cotton. Farmers are also trained on a host of natural pest management including the use of natural enemies such as parasitoids, insect viruses and entomopathogenic nematodes.

## Life after 2015 for Zimbabwe

The wide diversity of nematode pests calls for the implementation of an integrated approach to their management where both chemical and non-chemical alternatives to MBr should be employed. Iodomethane is a promising chemical alternative to MBr. Being non-ozone-depleting and having the same spectrum of pests controlled as MBr sets it apart of the other alternatives. However, its cost may be a limiting factor for Zimbabwe where pesticides are imported. Sodium azide would also be a good chemical alternative. However, its requirement of drip irrigation facilities makes it less adoptable by most small-scale farmers in Zimbabwe. While most chemical alternatives can never be like-for-like replacements for MBr, they will require modifications to achieve the same efficacy as MBr. A number of modifications have been done in the developed world and would need to be adapted for Zimbabwe. Most of the alternative chemicals discussed in this article are not yet registered in Zimbabwe.

Non-chemical alternatives like crop rotation, use of resistant cultivars and solarization are already being employed in Zimbabwe, even by the resource-poor farmers. Genetic engineering of crops has been promoted in Zimbabwe, with SIRDC at the forefront. Biofumigation trials are underway, and should be intensified so that local recommendations can be made to farmers. These methods are environmentally friendly and will help to achieve the desired goal of sustainable crop production and environmental protection.

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