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INVITED REVIEW

THE METHYL BROMIDE ISSUE: PROBLEMS AND POTENTIAL SOLUTIONS

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Dedicated to the memory of the late Dr. Avi Grinstein, a leading scientist and a friend

SUMMARY

Methyl bromide (MB) is the major soil fumigant in use worldwide and is highly effective in controlling a variety of soilborne pests, especially in intensive crops. However, due to its role in the depletion of the ozone layer, international agreement has been reached calling for its reduced consumption and complete phasing out by the year 2005 in developed countries. Hence there is a need to develop means of immediately reducing its dosage and consumption and to find alternatives to replace it. One way of reducing MB dosages without reducing its effectiveness in pest control can be achieved by using plastic sheets which are less impermeable to MB, thus delaying its escape to the atmosphere. Reduced dosages can also be achieved by improving technology of application and combining MB with other methods of control. Many potential and existing non-chemical and chemical alternatives to MB are available, but none can totally replace MB under all circumstances. Since MB affects a wide spectrum of pest control, integrated pest management (IPM) approach is called for. IPM aims at integrating all available, effective and environmentally acceptable methods of management, using them only when necessary while considering the environmental, social, economic and legal requirements with every alternative. Combing methods of control has many advantages and frequently results in improved control. Knowledge regarding the alternatives that will be developed has to be disseminated and transferred, and to this end, education and extension tools need to be further developed, in order to ascertain that the new alternatives are appropriately introduced for farmer's use.

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RIASSUNTO

BROMURO DI METILE: PROBLEMI E POSSIBILI SOLUZIONI. Il bromuro di metile (MB) è il fumigante maggiormente usato nel mondo ed è altamente efficace nel controllo di molti patogeni del suolo, specialmente di colture intensive. A causa dei suoi effetti negativi sullo strato di ozono, sono stati raggiunti accordi internazionali per ridurne immediatamente il consumo che dovrà cessare, nei paesi sviluppati, entro il 2005. Esiste, quindi, la necessità di sviluppare metodi che ne riducano il dosaggio e di trovare valide alternative. Un modo per ridurre i dosaggi di MB senza diminuirne l'efficacia prevede l'impiego di fogli di plastica, meno permeabili, che ne riducono la dispersione nell'atmosfera. Dosaggi ridotti possono essere raggiunti migliorando le tecnologie di applicazione e combinando l'MB con altri metodi di difesa. Esistono molte efficaci alternative, chimiche e non chimiche, ma nessuna di esse può sostituire l'MB in ogni situazione. Dato che l'MB agisce su un vasto spettro di patogeni, una valida alternativa potrebbe essere l'approccio integrato alla difesa delle colture (IPM). L'IPM prevede l'integrazione di metodi diversi di difesa, efficaci ed ambientalmente accettabili, intervenendo solo se necessario e tenendo nella debita considerazione gli aspetti ambientali, sociali e legali. L'integrazione di diversi metodi di difesa ha molti vantaggi e frequentemente fornisce ottimi risultati. La conoscenza relativa alle alternative che potranno essere sviluppate deve essere diffusa e, per questo scopo, sarà necessario sviluppare ulteriori strumenti di educazione e divulgazione al fine di garantire che le nuove strategie siano appropriatamente introdotte nella buona pratica agricola da parte degli agricoltori.

Key words: soil disinfestation, solarization, methyl bromide, IPM.

INTRODUCTION

Soil fumigation with methyl bromide (MB) is the major method used for controlling soilborne pests (this term includes all harmful organisms, *e.g.* pathogens, arthropods, weeds etc.), in intensive agriculture worldwide. However, since MB was listed under the Montreal Protocol in 1992 as an ozone depleting substance, regulations on its use and consumption has been imposed. In developed countries, MB consumption was started for reduction by 1999 and, except for certain exemptions yet undefined for critical uses, MB is to be phased out by the year 2005 (or earlier in certain countries). This is being done to protect the vital ozone layer in the stratosphere from depletion. This is a crucial issue since the ozone layer has already been depleted by a variety of substances such as chlorofluorocarbons. The role of MB in depleting the ozone layer, the chemical processes involved, and the various sources (in addition to its agricultural uses) and sinks of MB, will not be discussed in this article. They are covered in numerous other publications (*e.g.* UNEP, 1995; Bell *et al.*, 1996; Ristaino and Thomas 1997; UNEP, 1998). It should be mentioned that MB is released to the atmosphere from various sources, both anthropogenic and natural. This makes an evaluation of the relative contribution of soil fumigation with MB, to ozone depletion, complicated and even controversial. The impending phasing out of MB poses new and unprecedented challenges for the agricultural research community and the authorities, since many major crops, especially in intensive agriculture, have become totally dependent on MB use. To avoid an economic and social crisis, we have to develop, within a relatively short period, short-term solutions (to replace the already mandatorily reduced consumption of MB), as well as alternatives for its full replacement by 2005. We have to evaluate both existing and potential alternatives. Although, the major use of MB is for preplant soil fumigation (over 75%), it is also used for postharvest treatment of nonperishables and perishables and for quarantine purposes (Ristaino and Thomas, 1997; UNEP, 1998). In this article, I shall concentrate on MB for soil fumigation: the need for soil disinfestation and how to cope with MB replacement.

THE NEED FOR SOIL DISINFESTATION

Soil pests, such as bacteria, fungi, nematodes, parasitic plants, arthropods and other organisms frequently cause heavy losses to major crops, by affecting both yield and quality. In severe cases, they may totally destroy the crop, forcing the farmer to either abandon the land or shift to less susceptible, but often less profitable crops (Katan, 1996). In intensive agriculture, especially the protected crops are frequently or even continuously planted in the same land, thus leading to a rapid buildup of pest populations in the soil, especially those causing root diseases. There is, therefore, a need to develop effective control methods to ensure crop productivity and yield stability. In addition to being effective, these methods have to be economically, environmentally and technologically sound.

Soil disinfestation is one approach to controlling root diseases caused by soilborne pathogens, as well as other soilborne pests, and is especially common with high-value crops. It is a sophisticated, expensive but effective method of control, which has great advantages, but also some limitations. The basic principle is to eradicate a wide spectrum of harmful agents in the soil before planting, usually by drastic chemical or physical means, while attempting to minimize the damage to beneficial microorganisms. There are three approaches to soil disinfestation. The first two, steaming and fumigation, were developed about 130 years ago, and until recently, were the only existing approaches (Newhall, 1955; Katan, 1997). The third, relatively new approach is soil solarization (also called solar heating) (Katan, 1981; Katan and DeVay, 1991). The term soil sterilization should not be used to describe soil disinfestation since it is not correct, nor we aim to sterilize the soil, but rather reducing pest populations.

Chemical soil disinfestation by fumigants began from the early days in modern plant pathology. CS_2 was probably the first fumigant introduced (for controlling *Phylloxera* in vineyard soils), followed by chloropicrin after the First World War. MB's biocidal properties appear to have been discovered in the 40's and its use as a soil fumigant was rapidly expanded in the 50' and the 60'. There are many reasons for this. MB is versatile and effective against a broad spectrum of soil pests, including weeds. It is quite penetrative, thus easily reaching the pests in the soil, and it is also effective at relatively low temperatures. MB dissipates quickly after treatment. Because of decades of accumulated experience with this fumigant farmers can make optimal use of MB while avoiding situations in which it is not effective or has severe side effects. Experienced contractors and highly trained professional agents developed appropriate technologies and this biocide became acceptable and popular among farmers. This, despite the fact that MB has many disadvantages: it is highly toxic, it may reach the surface and ground water, bromide residue may accumulate in the edible parts of the plants, it is expensive, it affects beneficial microorganisms in the soil such as mycorrhizae, it may create a 'biological vacuum' in the soil and its application is complicated. Nevertheless, MB became the major soil disinfestant in the second half of this century, and only a few additional fumigants were developed. Various issues regarding MB are discussed in recently published books (UNEP, 1995; Bell *et al.,* 1996; UNEP, 1998).

It is amazing that during a period of over 100 years of accelerated development in crop protection sciences, involving many breakthroughs including the development of hundreds of highly effective pesticides, only three approaches for soil disinfestation have been developed and only a small number of fumigants have been used practically in a given period. Do the reasons for this situation stem from real difficulties involved in developing a soil pesticide or are they merely commercial? To what extent has the availability of such an effective fumigant as MB suppressed efforts to develop alternatives? We need to understand the reasons for this situation in order to avoid additional crisises in the future.

APPROACHES TO REDUCING MB CONSUMPTION: THE SHORT-TERM SOLUTION

MB dosages must be reduced to comply with the regulation dictating reduction in its consumption, for example, by 25% in 1999 and by 50% in 2001. There are several options for this purpose, which can be used, either alone or in combination. They are briefly described below.

THE USE OF IMPERMEABLE FILMS. MB is applied to the soil either manually or by mechanized injection. Plastic is used to cover the soil in order to delay the escape of the gas into the atmosphere. The commonly used films for MB fumigation, made of low or high-density polyethylene, provide a poor barrier for MB and enable its escape into the atmosphere within a short period after fumigation. Films which are less permeable to MB can minimize its escape, thereby maintaining a relatively higher MB concentration in the soil for longer periods. This would enable a reduction in dosage and consequently, diminished emission without reducing the effectiveness of the pest control it affords (Gullino *et al.,* 1996; Gamliel *et al.,* 1997). This approach is based on the assumption that concentration (C) of the fumigant x exposure time (T) (the CT value) is constant. Thus, increasing T enables a reduction in C while maintaing effectiveness of the pest control. Films which are impermeable or less permeable to MB are now commercially available and are already being used by farmers. Results from studies carried out in various countries show that various soilborne pathogens, including *Verticillium dahliae* in potato (Gamliel *et al.,* 1997b.), *Phytophthora capsici* in peppers (Cebolla *et al.,* 1996), *Rhizoctonia solani* and *Sclerotinia sclerotiorum* in lettuce and beans (Gullino *et al.,* 1996), were effectively controlled by a reduced dosage of MB under gas-impermeable films. The effectiveness of these films was demonstrated with all tested parameters: pathogen control, crop development, reduction in disease incidence and severity, increased yield and quality.

IMPROVED TECHNOLOGY OF APPLICATION. The use of impermeable films is an important factor in reducing the amount of MB used for soil fumigation and hence its emission into the atmosphere. Reduced dosages of MB can only be effective in pest control if the fumigant is uniformly applied and distributed to achieve the desired CT value throughout the soil profile. Therefore, MB dissipation through holes in the plastic sheets, from the edges of the mulched area and from other leakage points, should be avoided (Gamliel *et al.,* 1997). Appropriate technologies can further reduce MB emission and waste, while improving pest control.

COMBINING MB WITH OTHER CONTROL METHODS. The concept of integrating methods of control will be further discussed below. When MB is one of the components in a suitable appropriate combination of control methods, both effective pathogen control and reduced MB dosages can be achieved. Like MB, the application of solarization involves plastic mulching of the soil, and as such it is a natural candidate for such combinations. The combination of MB at reduced dosage with solarization resulted in effective control of Fusarium crown rot of tomato (Sivan and Chet, 1993), sudden wilt of melons (Gamliel *at al.,* 1994), Fusarium wilt of carnation (Cebolla *et al.,* 1996), and improved yield of gypsophila (Gamliel *et al.,* 1993). Combining MB with a biocontrol agent is a promising approach which, unfortunately has not been much exploited. The biocontrol agent can rapidly colonize the prefumigated soil and prevent its recontamination by pathogens. *Trichoderma harzianum* is an effective biocontrol agent against pathogenic soilborne fungi. Application of *T. harzianum* following fumigation at reduced dosage resulted in effective control of Fusarium crown rot of tomatoes (Sivan and Chet, 1993). Combining MB with *T. harzianum* enhanced the mortality of *Sclerotium rolfsii*, improved the control of this disease in tomato and increased yield (Elad *et al.,* 1982).

Since developing countries are allowed to use MB for a specified period beyond 2005, the above-described methods could be adopted by these countries to reduce its hazards and emission.

DEVELOPING CHEMICAL AND NONCHEMICAL ALTERNATIVES TO MB: THE LONG TERM SOLUTION

This is an exciting challenge which involves many real and inherent, as well as psychological difficulties. The inherent difficulties stem from the fact that MB is highly effective and has been successfully adapted (in some cases by trial and error) to various agricultural situations. Therefore, it became difficult to find an equivalent alternative. Although some alternatives, such as solarization and certain fumigants, are effective and are already being used by farmers on a commercial scale, none of the existing alternatives can replace MB under all circumstances. Thus, we have to adopt different solutions for different cropping systems.

Controlling a soilborne pest is more complicated than controlling a foliar one. The soilborne pest has to be reached, and its population considerably reduced, at all soil niches and depths. The control agent has to be able to withstand the physical, chemical and biological processes in the soil, while having only a minimal detrimental effect on soil biota. These difficulties are probably the major (but not the sole) reason for the extremely small number of methods currently used on a commercial basis for the control of soilborne pests, as compared to foliar pests. Moreover, many farmers believe that only pesticides are powerful and reliable control agents and are therefore reluctant to accept new technologies, especially if they are nonchemical. These farmers feel that replacing the familiar MB with a new alternative could be risky.

There are many potential alternatives to MB which are adequate for the management of various pests of different crops. These alternatives may differ in their level of effectiveness, environmental effect, cost, the experience behind them and other parameters and no attempt will be made here to describe them in detail. Some alternatives, such as solarization, soil and substrate steaming in greenhouse crops and certain combinations of fumigants are very effective, and in the appropriate situations are equivalent to MB. Other management methods, such as crop rotation and sanitation, cannot compete with MB; their role is rather to reduce the inoculum in the soil, thus minimizing the need for drastic and expensive disinfestation methods.

The major categories of alternatives are: (I) nonchemical alternatives: (*i*) breeding resistant cultivars and grafting; (*ii*) cultural methods such as crop rotation, flooding, sanitation, fallowing deepploughing, adjusting planting date and agricultural practices, soilless culture, etc. (Palti, 1981); (*iii*) physical methods, mainly steaming (Runia, 1983); (*iv*) soil solarization, namely, heating the soil by solar energy resulting in both physical and biological processes to control pathogens and other soil pests (Katan, 1981; Katan and DeVay, 1991; Garibaldi and Gullino, 1991); (*v*) biological control by treating the soil or the planting material with antagonists, by using organic amendments including composts, by using suppressive soils and by inducing resistance (Cook, 1983; Garibaldi *et al.,* 1990); (*vi*) biofumigation, namely, using organic amendments which produce volatiles, especially in combination with solarization or plastic mulching (Gamliel and Stapleton, 1997; UNEP 1998) (see below). (II) Chemical alternatives: these include mainly fumigants such as chloropicrin, 1,3-dichloropropene, methyl isothiocyanate generators, methyl iodide, formaldehyde, CS_2, anhydrous ammonia nematicides and others. Fungicides, insecticides and herbicides may be used for specific purposes. Frequently, chemicals are used in combination to improve their effectiveness and expand their spectrum of control. More details are given in various publications, *e.g.* UNEP, 1995, 1998.

Attempts are also being made to use naturally occurring compounds.

HOW TO ACHIEVE A WIDE SPECTRUM OF CONTROL WITHOUT MB: THE IPM APPROACH

A very obvious advantage of MB is its capacity to control a wide spectrum of pests. We should not replace MB with another highly toxic broad-spectrum fumigant, nor will such a chemical be available any time in the near future. We therefore need to adopt an integrated pest management (IPM) approach with necessary modifications, as needed, something which should have been done a long time ago. It appears that the convenience of MB availability did not encourage the scientific community, or the authorities, to seek alternatives to MB before the ozone-depletion crisis. We did not have the vision to foresee and prepare for unpleasant scenarios. IPM integrates all available acceptable pest management methods (Katan, 1996). It can be regarded therefore as an ecologically based strategy equivalent to the broad spectrum control achieved by MB. The basic principles are summarized as follows: (*i*) integrating all available effective approaches for pest control; (*ii*) aiming at effective, but not necessary an absolute, control; (*iii*) reducing, not necessary a total elimination, of pesticide usage; (*iv*) environmental considerations; (*v*) monitoring pest population in order to control only when necessary; (*vi*) considering all the pests of the crop, not only the one against which we target our main efforts; (*vii*) economic, social and legal considerations.

These parameters should be used as guidelines in evaluating alternatives to MB or any other pest management method.

Combining methods of control is the heart and the pillar of IPM. If we accept the fact that we need to diversify disease management techniques, then we have to combine or alternate methods of control. A suitable combination of pest management methods can provide: (*i*) improved control; (*ii*) a wider spectrum of control; (*iii*) reduction of pesticide dosage; (*iv*) long-term effects; (*v*) an avoidance or delaying of negative side effects, *e.g.* resistance to pesticides or negative effects on mycorrhizae.

Various methods can be combined. There are many cases of good results obtained by combining methods of control (*e.g.* Ben-Yephet *et al.,* 1988; Minuto *et al.,* 1995). Pesticides at reduced dosages can also be considered. For example, a tomato cultivar which is resistant to a variety of fungal pathogens might be planted in a soil treated with a nematicide and herbicide. This could provide pest control comparable to that of MB, probably at a lower cost. It is not anticipated that a single alternative will alone substitute for MB. However, in most cases, a combination of methods, tailored to specific crops, sites and other variables, can replace MB (UNEP, 1995).

BIOFUMIGATION. When organic amendments which release volatile components that are toxic to pathogens are combined with solarization, the plastic tarp prevents or delays the escape of the volatiles and increases their effectiveness. This is a very good example of a suitable combination of methods of control. This has been demonstrated by combining solarization with many organic amendments such as chicken compost which was very effective in controlling the root-knot nematode and increased the yield of lettuce over two successive seasons (Gamliel and Stapleton, 1997c).

Combining methods of control is based on the weakening phenomenon. When a propagule of a pathogen is exposed to a sublethal dosage of a killing agent, it is not killed immediately after treatment. However, the propagule is damaged and weakened, and becomes more vulnerable to antagonistic microorganisms in the environment (Freeman and Katan, 1988). As a result, the pathogen population declines faster than the nontreated population, namely, an induced biological control. This phenomenon of enhanced decline of pathogen population is probably connected with the synergistic effects frequently observed with combined treatments.

EDUCATION, EXTENSION, TRAINING, KNOWLEDGE TRANSFER, TECHNOLOGICAL ADJUSTMENT AND IMPLEMENTATION

Introducing a new agricultural technology to farmers requires coordinated research and development efforts. Research which demonstrates the effectiveness and reproducibility of the new technology under field conditions, and also backs the fieldwork with fundamental research on the mode of action, is only a first step. The new method needs to be tested under realistic conditions at an advanced stage of development and its reproducibility verified before it is recommended for use. An upscaling program evaluating the effectiveness of the method from preliminary laboratory tests to farmers' plots should be designed, in order to avoid failures and economic losses resulting from introducing premature, new technologies for commercial use. When necessary, the new alternative has to be modified and adapted to each cropping system or climatic region. Technologies related to the method's implementation should also be developed. Extension specialists who are experts in training and economists should be partners in these tasks (Katan, 1993). Demonstration plots and extension tools, such as leaflets, video films etc., prepared by professionals, are essential. Farmers have to be shown that absolute control is usually not justified and in fact, might be environmentally and economically costly. Pest management has to be carried out only when necessary. Therefore, methods for monitoring populations of soilborne pests and evaluating their impact should be developed and routinely used. It is possible that in cases where a complex of pathogens is involved, one pathogen may escape the alternative method which replaced MB and therefore its population rapidly increases. It is essential therefore to monitor the treated fields to detect possible outbreaks of new pests. Most of the new methods require a suitable technology for their application. The technology has to be reliable, feasible and economically valid to be accepted by the farmers. In the past, these steps, which are beyond the research per se, have often been overlooked or neglected, leading to a loss of potential good control methods, due to failure in implementation. Frequently these are unnecessary failures which could have been avoided. Factors affecting acceptance of alternatives include local availability, registration status, costs, labour inputs and efficacy against target pests (UNEP, 1998).

CONCLUDING REMARKS

The task of developing effective, economically feasible and safe alternatives to MB for a variety of crops, is difficult and complex, but seems attainable if appropriate strategies are planned and the required heavy investment in research, development and manpower is provided. It is not known, however, whether we shall be able to provide MB alternatives for all major crops by 2005. Success in this task will serve as a model for solving similar problems with other pesticides in the future, while failure will result in severe economic losses. We should make every effort to avoid replacing MB with chemicals or other alternatives which may have negative or unknown environmental and human health consequences. It is essential to avoid substitution of MB with methods which may be more damaging to human health or the environment than MB itself (UNEP, 1995).

Certain uses of MB are of crucial importance. This is especially true with the production of propagation materials, *e.g.* nurseries, seeds, bulbs, etc. MB reduces the risk of disseminating pests to new areas with the propagation material. Therefore, in such cases we have to ascertain that MB is replaced only by a method which is at least equally effective at pest control. Failure to do this will result in the introduction of new pests to new regions and will force us to use pesticides to eradicate the introduced pest at an unnecessary environmental, as well as economic cost. There are cases for which satisfactory alternatives are not available. These include propagation material, replant problems which are especially crucial in areas with limited land availability, and possibly other cases. Such cases should be given priority in research, and until satisfactory solutions are found, they should be included in the exemptions regarding MB usage. If an alternative is effective in controlling certain pathogens in a specific area, this does not mean that the same solution will apply to other areas. It is hoped that the concentrated efforts by the international research community will create new approaches and ideas, and will also lead to a reassessment of traditional but good methods, such as crop rotation, which have been unjustifiably neglected in the past. Last but not least, we should avoid dependence on a single pesticide. Increased investment in research, development and technology transfer are necessary to fully implement alternative pest management systems for MB.

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