ISSN 1899-5772

Journal of Agribusiness and Rural Development

www.jard.edu.pl

1(15) 2010, 55-65

COMPARATIVE YIELD EFFICIENCIES OF METHYL BROMIDE SUBSTITUTE FUMIGANTS AND MULCHING SYSTEMS FOR PEPPER PRODUCTION IN THE SOUTHEAST

Esendugue Greg Fonsah[1], Yingzhuo Yu[2], Cesar Escalante[3], A Stanley Culpepper[4], Xiaohui (Sarah) Deng[5]

[1, 2, 3, 4]University of Georgia

[5]California State University

Abstract. Methyl Bromide (MB) is one of the most effective and widely used commercial chemicals in agriculture and non-agricultural sectors respectively. The decision to phase-out MB by 2005 set the stage for scientists to come up with a non-less-toxic replacement alternative or combinations thereof. This study focused on comparing yield efficiencies of different MB substitute fumigants and mulching systems for pepper production in the Southeast. Results of this study depicted that pepper production is potentially maximized under the tel-pic-vap treatment which is the only fumigation method that yielded significant differences relative to at least one other alternative approach.

Key words: Methyl Bromide, Replacement alternatives, Fumigants, pepper, mulch, yield, efficiency

INTRODUCTION

For almost half a century, Methyl Bromide (MB) has been the most widely used commercial chemical to regulate multiple pests such as fungi, bacteria, soil-borne viruses, insects, mites, nematodes and rodents. Because of its multiple functions, MB is also used as a soil fumigant, as disinfectant for "durable and perishable (goods), buildings, ships and aircraft" and to subdue several unwanted plants and seeds in soils [Byrd et al. 2006, 2007, Culpepper and Langston 2005, The Montreal Protocol... 1998].

Adres do korespondencji – Corresponding author: prof. Esendugue Greg Fonsah, Department of Ag & Applied Economics, University of Georgia, P.O. Box 1209, 15 RDC Rd, Tifton, GA 31793, e-mail: gfonsah@uga.edu or gregfonsah@yahoo.com

MB is undeniably one of the effective compounds/products used for integrated pest management. However and despite its multifaceted importance, MB was listed as an ozone depleting substance in 1992. According to the Montreal Protocol, the production of all depleting substances including MB was to be discontinued by January 1, 2005. In 1996, out of 71,425 tons of MB produced worldwide, 54,283 tons (76%) was used for agricultural production and/or soil fumigant, 15,000 tons (4.8%) was used for "quarantine/pre-shipment" (QPS), 2,759 tons (3.9%) for "feedstock for chemical synthesis", and 6,428 tons (9%) for "perishable commodities" [Byrd et al. 2006, 2007, The Montreal Protocol... 1998].

According to Haire [2003], about a third of the total world production of MB is Consumed by the United States with an estimated annual consumption rate of 21,000 tons. Approximately 75% of the U.S. consumption is by two major fruit and vegetable producing states, California and Florida [Carpenter et al. 2000, Byrd et al. 2006]. In agricultural production, MB is used as soil fumigant to eradicate noxious weeds, pests such as nematodes and soil-borne diseases [Culpepper and Langston 2005].

The recommendation of the 39 members of the Methyl Bromide Technical Options Committee (MBTOC) stipulated that the non-Article 5(1) parties, i.e. the industrialized nations which include the United States must reduce the use of this toxic chemical by 25% of the 1991 "base level" of 71,425 tons by January 1, 1999. Another 50% reduction was scheduled for January 1, 2001 and 70% reduction by January 1, 2003. A total eradication was set for January 1, 2005 "with provision for exemptions for any critical uses". Georgia and other states in U.S. did apply for the critical use exemption. The Protocol defined "critical" as growers not having a readily available replacement, unable to carry out agricultural production without MB and proof of economic hardship caused by the absence of MB [Byrd et al. 2006, 2007, The Montreal Protocol... 1998].

As a result of these problems, there was a desperate need for an alternative to MB use. As earlier mentioned, the United States is not only ranked 1st in ag-production but also in the utilization of MB. Thus, the objective of this study was to use field trials and econometrics analysis to evaluate various ozone layer friendly fumigants that would solely or in combination provide similar or better benefits in terms of controlling soil-borne diseases, nematodes, nutsedge and yield to be utilized as a replacement for MB.

A baseline study forecast that the United States horticultural production, including vegetables, fruit and nuts, and ornamental plants that was supported by the use of MB in the past will be worth about $50 billion in 2008 and close to $70 billion in 2016. Without MB or its substitute, this level of production would be impossible. The fruit and vegetable industry alone is expected to contribute over $30 billion in 2008 and over $40 billion in 2016 [Lucier and Jerardo 2006]. In the state of Georgia, the fruit and vegetable industry is expected to contribute over $1.1 billion in farm gate value and it was ranked 2nd amongst the 2006 Georgia top ten commodities [Fonsah 2008, Boatright and McKissick 2006]. Another recent study showed that fruit and vegetable contributed the lion's share, over 29% of the U.S. farm cash receipt from 2002 to 2006 and about 20% of total U.S. agricultural exports in the same time period [Lucier et al. 2006]. Because of the importance of the U.S. fruit and vegetables and the Montreal Protocol policy aimed at completely discontinuing the utilization and production of MB, several studies have been done to search for alternatives.

Studies for MB replacement options in California and Florida concentrated on strawberry and tomato, commodities for which these two states are major producers and exporters [Vegetables... 2001]. Because of the climatological and ecological conditions, the presence of yellow and purple nutsedge weeds have made it impossible to cultivate vegetables such as pepper, tomato, cucumber, squash, zucchini, cantaloupe and eggplant in Georgia and Florida in particular and the southeast region at large. As a result, studies on MB replacement alternatives there have focused on different plasticulture techniques such as low density polyethylene (LDPE), Metalized Smooth, Metalized Embossed and Virtually Impermeable (VIF) mulching options [Culpepper and Langston 2005, 2006, Gilreath and Santos 2004]. Other studies focused on testing of various equipment needed for the application of possible alternatives that would provide results comparable to MB [Sumner 2005] and whether the equipment used to apply MB can be utilized to apply alternative fumigants such as Telone II, Chloropicrin and Metam Sodium with slight modifications [Sumner 2007]. Economic studies aimed at determining the profitability margins of bell pepper production in Georgia were conducted [Fonsah et al. 2005, Fonsah 2006]. Furthermore financial efficiency of implementing MB alternatives in bell pepper production in Georgia and an analysis of the optimal production and economic viability of different fumigant-herbicide alternative systems compared to MB in the production of pepper in Georgia were also conducted [Byrd et al. 2006, 2007, Fonsah et al. 2005].

It is worth mentioning that most MB studies in Georgia are focused on pepper because pepper is more vulnerable to yellow and purple nutsedge weeds, nematodes and other soil-borne diseases. Therefore, it is likely that any MB replacement alternative or combination that works for pepper would also work for the rest of the vegetable crops [Culpepper and Langston 2006, personal conversation]. Furthermore, pepper is a major commercial crop in Georgia contributing 10.11% of total vegetable farm gate value and ranked 3rd among the 2006 top ten vegetables in the state. Nationwide, per capita consumption of pepper has increased from 6.4-7.8 pounds farm-weight from 1998 to 2007. Georgia is ranked 3rd in the United States after California and Florida in pepper cultivation, producing 1.1 million pounds in 2006 and 2007 respectively [Boatright and McKissick 2006, Lucier and Jerardo 2007, Quick Stats 2008]. Although Georgia harvested area declined from 5,500 acres in 2000 to 4,100 acres in 2007, total yield and prices have increased dramatically from 170,000 to 280,000 pounds/acre and from $26.60 to $35.00 per cwt in the same time period [Quick Stats 2008].

All these positive economic indicators show the importance of pepper to the Georgia economy and why it is of vital importance to identify alternative replacement for MB not only for the state of Georgia but the Southeast region and the entire United States. However, there is a more crucial reason why a replacement or a combination thereof is absolutely necessary. According to Kelley [2009], The United States Environmental Protection Agency (EPA) made it clear that "vegetable growers' biggest obstacle to methyl bromide (MB) access is not the international body [anymore] but the domestic authority". Although the critical use exemption applications for 2009 were approved, both the production and stock are declining. According to EPA, the available stocks of 16.42 metric tons (MT) in 2003 had declined to only 6.46 MT in 2007. In 2009, the U.S. requested 16.7% of the 1991 baseline and although only 15.5% from new production was granted, EPA slashed the quantity to 6.3% from new production and insisted that 10.1% should be provided from existing stock of which the stock is also depleted. The bottom line is there will be very little MB available for 2009 and nothing for 2010. As a result scientists are pressed to find the best alternatives and vegetable growers have no choice but to adopt the new technology. More-so, due to this shortage, the price for MB has also skyrocketed [Kelley 2009].

This study utilizes multiple factor analysis techniques to analyze the relative effects on pepper production yields of three varying factors used in the production experiments: fumigant, mulching and harvest time. This study will utilize experimental data collected from various production treatments involving combinations of alternative fumigants and mulching methods that were conducted in 2006 in TyTy, Georgia.

The following sections provide more detailed discussions of the field experiments, the analytical framework used in evaluating comparative yield efficiencies, and this study's conclusions.

MATERIALS AND METHODS

The experiment was conducted in 2006 near TyTy, Georgia (31.50911°, –83.64813°) on a Tifton loamy sand (kaolinthic, thermic Plinthic Kandiudults; 88% sand, 8% silt, 4% clay, 0.9% organic matter; pH 6.4), which is typical of Georgia's vegetable producing region. The study site was mechanically cultivated prior to planting using a tandem disk followed by a moldboard plow deep turning to a depth of 34 cm. A field cultivator with double rolling baskets and S-tine harrows finalized field preparation.

Eight fumigant and four mulch treatments were combined factorially and arranged as a randomized complete block with 3 replications. Fumigant options included no fumigant, methyl iodide plus chloropicrin (MIDAS) in a 50:50 mixture applied at 390 kg/ha; methyl bromide plus chloropicrin (MB) in a 67:33 mixture at 390 kg/ha; dimethyl disulfide plus chloropicrin (DMDS) in a 79:21 mixture at 700 L/ha, 1,3-dichloropropene plus chloropicrin (Pic Chlor 60) in a 40:60 mixture at either 280 or 448 kg/ha; 1,3-dichloropropene at 100 L/ha followed by (fb) chloropicrin at 168 kg/ha (T2 fb Pic); and 1,3-dichloropropene at 100 L/ha fb chloropicrin at 168 kg/ha fb metam sodium at 700 L/ha (3-WAY). Mulch options included 0.032 mm (1.25 mil) traditional low density black on black polyethylene mulch, smooth low density black on black polyethylene mulch, high barrier black on black Blockade mulch, and a high barrier silver on black metalized mulch.

All of the fumigants were applied on February 22. For the 3-WAY and T2 fb Pic systems, 1,3-dichloropropene was injected 40 cm below the soil using a Yetter 76 cm Avenger Coulter system having 3 blades spaced 26 cm apart prior to bed formation. Planting beds (15 cm ht. and 81cm wid.) were prepared using a pre-bedder that was also equipped with three shanks placed 28-cm apart; the remaining fumigants, except metam sodium, were injected 20-cm below the bed top via the shanks. The pre-bedder was followed by a super-bedder plastic layer that injected metam soidum 10 cm below the bed surface and also inserted one line of drip irrigation tubing 2 cm below the bed top and covered all beds with mulch. Metam sodium injections in the 3-WAY system were made through eight coulter units spaced 10 cm apart on the front of the super bedder. Except for metam sodium, fumigant flow was pressurized by N and was regulated by a calibrated flow meter. Metam sodium was injected using an electric pump[13] with lines equipped with Teejet size 46 orifice disks. All Fumigants were applied as an in-bed banded treatment. All of the beds were covered with plastic mulch within five minutes of the fumigant injection.

Bell peppers ('Heritage') were transplanted on March 13. Peppers were planted in double rows with plants spaced 30 cm apart along the row length and 38 cm apart across the bed top. Each plot was 10 m in length; bed centers were 182 cm apart. Foliar insecticide and fungicide sprays were applied weekly starting 3 weeks after planting. Fertilizer was applied preplant prior to bed formation. Additional fertilizer was injected through the drip injection. General pest control and fertilization practices followed University of Georgia recommendations (Kelley and Boyhan 2006). Bell pepper were staked and strung once they reached 22 cm in height. Bell peppers were harvested once per week for five consecutive weeks beginning on May 26. At harvest, U.S. Fancy marketable pepper fruit were processed and sized into five categories including jumbo (9.5 cm by >8.9 cm), extra-large (8.9 cm by 8.9 cm), large (8.2 cm by 7.6 cm), medium (7.6 cm by 6.4cm) and small (6.4 cm by 5 cm) [United States Standards... 2007].

Visual crop injury estimates, where 0 = no crop injury and 100 = complete crop death, were taken throughout the season [Frans et al. 1986]. The heights of 10 consecutive pepper plants per plot were measured 5 wk after planting. Counts of emerged nutsedge plants growing through the polyethylene mulch or through the plant hole were made 3 and 8 wk after planting for each entire plot. No other weeds were present in the experimental area. Furthermore, a multiple factor analysis was adopted to statistically explain the variability in the various alternative-fumigant mulching techniques.

ANALYTICAL MODEL

This study utilizes multiple factor analysis techniques to analyze the relative effects on pepper production yields of three varying factors used in the production experiments: fumigant, mulching and harvest time. Factor analysis is a method for examining how underlying constructs or factors affect the responses on one or several measured variables. This analysis is performed by examining correlation (or covariance) patterns between observed measures. Highly correlated measures are likely influenced by the same factors while relatively uncorrelated measures are probably influenced by different factors.

In this analysis, the three-factor model is defined by the following equation:

$$y_{ijkr} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkr} \quad (1)$$

$$\text{s.t.} \sum_{i=1}^{a}\alpha_i = 0,\ \sum_{j=1}^{b}\beta_j = 0,\ \sum_{k=1}^{c}\gamma_k = 0,\ \sum_{i=1}^{a}(\alpha\beta)_{ij} = 0,\ \sum_{j=1}^{b}(\alpha\beta)_{ij} = 0 \quad (2)$$

$$\sum_{i=1}^{a}(\alpha\gamma)_{ik} = 0,\ \sum_{k=1}^{c}(\alpha\gamma)_{ik} = 0,\ \sum_{j=1}^{b}(\beta\gamma)_{jk} = 0,\ \sum_{k=1}^{c}(\beta\gamma)_{jk} = 0,\ \sum_{i=1}^{a}(\alpha\beta\gamma)_{ijk} = 0 \quad (3)$$

$$\sum_{j=1}^{b}(\alpha\beta\gamma)_{ijk} = 0,\ \sum_{k=1}^{c}(\alpha\beta\gamma)_{ijk} = 0 \quad (4)$$

where the subscripts $i = 1...a$ refers to the α levels for factor one, fumigant; $j = 1...b$ refers to the β levels for factor two, mulch; $k = 1...c$ refers to the γ levels for factor three, harvest time; and $r = 1...n_{ijk}$ which refers to the numbers of replicates at each treatment represented by the interactions of the three factors respectively. The response variable in this model is y_{ijkr} which represents experimental pepper yields. Since there are no replicates in each treatment in this study, the subscript r will be omitted in equation (1). Accordingly, the three factors' interaction term $(\alpha\beta\gamma)_{ijk}$ will also be dropped from the equation due to lack of the degrees of freedom.

In this econometric analysis, all eight fumigation methods were considered: no fumigant (na); methyl iodide plus chloropicrin (midas); methyl bromide plus chloropicrin (mb); dimethyl disulfide plus chloropicrin (dmds); 1,3-dichloropropene plus chloropicrin plus metam sodium (tel-pic-vap); chloropicrin (pic-400); 1,3-dichloropropene plus chloropicrin (tel-pic) and chloropicrin (pic-250). Each of these fumigation methods is combined with one of four mulching methods, namely, traditional low density black on black polyethylene mulch (ldpe), smooth low density black on black polyethylene mulch (metal), high barrier black on black Blockade mulch (smooth) and a high barrier silver on black metalized mulch (vif) respectively. There are also five harvest periods considered in the analysis. The inclusion of the harvest time factor is intended to capture the effects of variable growing conditions associated with each harvest period on the magnitude of yields realized at each harvest point.

RESULTS

In determining the relevance of the analytical approach, the F value for this study's three-factor ANOVA model (Table 1) is significantly different from 0 at the 99% confidence level. The results in Table 1 also establish the separate significance of all three factors (fumigant, mulch and harvest time) in explaining variations in pepper yields. Two of three interaction effects, the interaction of fumigant with both mulch and harvest time, also yielded significant results. The interaction effect between fumigant and mulch, however, is not significant.

Additional calculations were made to verify the yield effect under two scenarios (with and without fumigation). The resulting mean difference of yields under such scenarios (14.36 lbs) is significantly different from zero, thereby suggesting that fumigation enhances production yields. On average, pepper yields under production methods that include fumigation are 14.36 lbs higher than yields realized in the absence of fumigation. Table 2 examines the relative yield dominance of each fumigation method. Based on these pair-wise analyses, pepper production is potentially maximized under the tel-pic-vap treatment, which is the only fumigation method that yielded significant differences relative to at least one other alternative approach. Specifically, high production potential can be realized under tel-pic-vap relative to the na and midas treatments. The tel-pic-vap method produces an average yield of 31.05 lbs while the least productive method, na, produces only 26.80 lbs of pepper yield. There are no observed significant differences between the tel-pic-vap and any of the other five fumigation methods. Moreover, the cross-effects among midas, mb, dmds, pic400, tel-pic, pic250 are all insignificant.

Table 1. Decomposition of factor effects and model's analysis of variance

Source	Degrees of freedom	Type III Sum of Squares	Mean Square	F Value	Pr > F
Fumigant	7	235.66	33.67	2.27	0.0365
Mulch	3	197.47	65.827	4.43	0.0061
Harv	4	29 391.75	7 347.94	494.78	< 0.0001
Fumigant×mulch	21	225.41	10.734	0.72	0.7983
Fumigant×harv	28	2 482.48	88.66	5.97	< 0.0001
Mulch×harv	12	1 100.47	91.71	6.18	< 0.0001
Analysis of Variance (Model)					
Model	75	33 633.24	448.44	30.2	< 0.0001
Error	84	1 247.47	14.85		
Corrected total	159	34 880.71			

Table 2. Paired comparisons of relative treatment effects on production of fumigant methods

i/j	na	midas	mb	dmds	tel-pic--vap	pic-400	tel-pic	pic250	Production mean
na	NA	0	0	0	*	0	0	0	26.80
midas	0	NA	0	0	*	0	0	0	27.31
mb	0	0	NA	0	0	0	0	0	28.55
dmds	0	0	0	NA	0	0	0	0	29.15
tel-pic-vap	0	0	0	0	NA	0	0	0	31.05
pic400	0	0	0	0	0	NA	0	0	28.67
tel-pic	0	0	0	0	0	0	NA	0	28.08
pic250	0	0	0	0	0	0	0	NA	29.16

Notes: * indicates a significant difference at the 95% confidence level in the production mean between a pair of fumigant methods.

0 indicates the absence of significant production mean differences at the same confidence limit.

The same analytical approach is applied to analyze the relative strengths of the mulching methods. Based on the summary in Table 3, the metal mulch method can maximize yield potential as it dominates two other alternative methods (vif and ldpe). The metal mulch method produces an average yield of 30.42 lbs while the vif method is the least productive with 27.45 lbs of pepper yield. The relative effects on pepper yield among ldpe, smooth, and vif methods are not significantly different.

Table 3. Paired comparisons of relative treatment effects on production of mulching methods

i/j	ldpe	metal	smooth	vif	Production mean
ldpe	NA	*	0	0	28.08
metal	0	NA	0	0	30.42
smooth	0	0	NA	0	28.43
vif	0	*	0	NA	27.45

Notes: * indicates a significant difference at the 95% confidence level in the production mean between a pair of fumigant methods.
0 indicates the absence of significant production mean differences at the same confidence limit.

In terms of harvest times, the 2nd harvest point potentially maximizes pepper yields at 47.95 lbs. while the 1st harvest period produces the lowest mean yield and has been dominated by the other harvest points (Table 4).

Table 4. Paired comparisons of treatment effects on production of harvest times

i/j	1	2	3	4	5	Production mean
1	NA	*	*	*	*	6.03
2	0	NA	0	0	0	47.95
3	0	*	NA	0	0	31.82
4	0	*	0	NA	0	32.09
5	0	*	*	*	NA	25.08

Notes: * indicates a significant difference at the 95% confidence level in the production mean between a pair of harvest times.
0 indicates the absence of significant production mean differences at the same confidence limit.

CONCLUSION

The world's agricultural community has benefitted from the use of Methyl Bromide (MB) for over half a century. At the national level, the over $50 billion U.S. horticultural industry which is estimated to increase to $70 billion in 2016 will be hard hit without MB or a replacement. The state of Georgia, where the fruit and vegetable industry is ranked 2nd amongst the Georgia top ten commodities is expected to contribute over $1.1 billion in farm gate value. Due to the importance of the U.S. horticulture industry and the apparent Montreal Protocol policy aimed at completely discontinuing the utilization and production of MB, the objective of this study was the adoption of field trials and econometrics analysis to determine which ozone layer friendly fumigants, would solely or in combination provide similar or better benefits to agriculture in terms of controlling soil-borne diseases, nematodes, nutsedges and yield to replace MB.

Eight fumigant and four mulch treatments were combined factorially and arranged as a randomized complete block with 3 replications and all of the fumigants were applied on February 22 whereas Bell pepper ('Heritage') were transplanted on March 13. This study utilizes multiple factor analysis techniques to analyze the relative effects on pepper production yields of three varying factors used in the production experiments: fumigant, mulching and harvest time.

The results of multiple factor analyses shows that the F value for this study's three-factor ANOVA model is significantly different from 0 at the 99% confidence level, hence, establishing its usefulness in explaining differences among the different experimental treatments (three underlying constructs or variables). The result further establishes the separate significance of all three factors (fumigant, mulch and harvest time) in explaining variations in pepper yields. In addition, although two of three interaction effects, i.e. the interaction of fumigant with both mulch and harvest time, also yielded significant results, the interaction effect between fumigant and mulch was not significant. On verifying the yield effect under two scenarios, i.e. with and without fumigation, the mean difference of yields (14.36 lbs) was significantly different from zero and hence, led us to the conclusion that fumigation enhances production yields. On average, pepper yields under production methods that include fumigation are 14.36 more than yields realized in the absence of fumigation. Further examination of the relative yield dominance of each fumigation technique vis-à-vis another alternative fumigation method depicted that based on these pair-wise analyses, pepper production is potentially maximized under the tel-pic-vap treatment, which is the only fumigation method that yielded significant differences relative to at least one other alternative approach. Since our study has established the yield potential of eight different fumigation techniques, a follow up study to establish which of these production systems provide maximum profitability and financial benefits to growers is strongly recommended.

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EFEKT SUBSTYTUCJI BROMKU METYLU (MB) W FUMIGACJI W SIEWIE BEZPOŚREDNIM W UPRAWIE PIEPRZU NA POŁUDNIOWYM WSCHODZIE

Streszczenie. Bromek metylu (MB) jest jedną z najbardziej skutecznych i powszechnie stosowanych substancji chemicznych w rolnictwie i niektórych sektorach pozarolniczych. Decyzja w sprawie wycofania MB do 2005 roku zainspirowała naukowców do wynalezienia mniej toksycznych alternatyw dla tej substancji. Niniejsze opracowanie koncentruje się na porównywaniu efektywności fumigantów różnych alternatyw MB.

Słowa kluczowe: bromek metylu, metody alternatywne fumiganty, pieprz, wydajność, efektywność

Zaakceptowano do druku – Accepted for print: 1.09.2010

Do cytowania – For citation: Fonsah E.G., Yu Y., Escalante C., Culpepper S., Deng X., 2010. Comparative yield efficiencies of methyl bromide substitute fumigants and mulching systems for pepper production in the southeast. J. Agribus. Rural Dev. 1(15), 55-65.