Economics of fumigation in tomato production: the impact of methyl bromide phase-out on the Florida tomato industry

RESEARCH ARTICLE

Xiang Cao[a], Zhengfei Guan[b], Gary E. Vallad[c], and Feng Wu[①d]

[a] PhD student, Virginia Tech, Department of Agricultural and Applied Economics, Hutcheson Hall, Blacksburg, VA 24061, USA

[b] Assistant Professor, [c] Associate Professor, [d] Research Assistant Scientist, University of Florida, Gulf Coast Research and Education Center, 14625 CR 672, Wimauma, FL 33598, USA

Abstract

The Florida tomato industry is facing challenges of increased production costs and decreased yields resulting from the methyl bromide (MBr) phase-out under the Montreal Protocol for environmental concerns. MBr and several accepted alternative soil fumigant systems are analyzed in this study from an economic perspective. This article focuses on identifying optimal fumigant systems by analyzing the cost effectiveness and economic risk associated with MBr and several other commercially available soil fumigant systems using data collected from scientific field trials. The results obtained show that a 67:33 formulation of MBr: chloropicrin is the most cost-effective treatment, and no alternative fumigant systems investigated can substitute MBr cost-effectively in Florida tomato production. The analysis indicated that switching from MBr (67:33) to the new industry standard PicChlor 60 approximately resulted in a loss of $3,569 per acre in gross revenue and $1,656 per acre in profit using market prices in the 2013/14 season. Higher market prices would further increase the loss.

①Corresponding author: fengwu@ufl.edu

1. Introduction

Methyl bromide (bromomethane, CH_3Br) used to be the most powerful and popular soil fumigant. In the past, most US agricultural producers utilized methyl bromide (MBr) as the primary fumigant due to its ease of application and high efficacy. In Florida, fresh tomatoes, peppers, and strawberries accounted for 50%, 32%, and 12% of total MBr pre-plant usage in respective crops in the United States before 2000 (Osteen, 2000). However, MBr also damages the ozone layer. In 1992, MBr was officially listed as a stratospheric ozone-depleting substance under the Montreal Protocol, a global agreement to protect the earth's ozone layer and reduce the risk of ultraviolet radiation exposure. In 1997, the Montreal Protocol required that developed countries eliminate all MBr fumigants by 2005, with few exceptions.[1]

Since the MBr phase-out, US growers have gradually transitioned to other fumigants in place of MBr, but these alternative fumigants lack the same consistent, broad-spectrum effectiveness and low cost as MBr. The alternative fumigants currently used in US agriculture are also more sensitive to environmental factors, such as soil moisture and temperature, which can limit efficacy during adverse periods of weather. These shortcomings have required the industry to combine 2 to 3 alternatives into a fumigant system to replace MBr. The MBr phase-out has placed tremendous pressure on the US fruit and vegetable industry. Florida is the largest fresh market tomato supplier in the nation and has suffered from increased production costs and decreased yields. Economically, the MBr phase-out has caused substantial losses to Florida tomato growers. An *ex ante* analysis forecasted a loss of $68.8 million (VanSickle *et al.*, 2000). No scientific *ex post* estimates of losses are available in the literature to date. According to the fumigation usage survey conducted in 2012 by the Florida Tomato Exchange and the Florida Fruit and Vegetable Association, the transition to the alternative fumigants has caused up to a 20% yield loss compared to MBr treatments, and growers have suffered from escalating costs resulting from additional pesticide inputs needed to complement these alternative fumigants. The MBr phase-out has created technological shocks throughout the fruit and vegetable industry, which, together with intensifying Mexican competition (Suh *et al.*, 2017; Wu *et al.*, 2018) and labor shortages (Guan *et al.*, 2015; Roka and Guan, 2018), has created serious challenges for the industry. Mexico, as a developing country, is subject to a longer phase-out which lasted until 2015 while tomato production in the country is also less susceptible to pest and disease issues, creating a competitive advantage in international trade.[2] According to statistics from the National Agricultural Statistics Service of the USDA (USDA/NASS, 2013), Florida fresh tomato production decreased from 45 thousand acres in 2001 to 29 thousand acres in 2012, and the current acreage remains low compared to early years. The farm gate value of the industry slumped from $620 million in 2010 to $270 million in 2012 and further decreased to $260 million in 2017.

Against such a background, we conducted a field experiment in fall 2013 to: (1) examine the economic performance or viability of alternative fumigant systems and identify economically optimal fumigant systems for the Florida tomato industry; (2) analyze the economic impact of the MBr phase-out; the *ex post* economic analysis will generate information and provide insights for policy makers to evaluate program impact and make informed decisions in relation to fumigation and pest management policy, which is critical for the industry. The fumigant performance analysis will account for both the treatment effects and the consistency (volatility) of the effects, and the economic impact analysis will focus on the effect on farm income.

Prior economic studies mostly investigated the effect of MBr and its alternatives on pepper production in Georgia, with an exception of Sydorovych *et al.* (2008). Byrd *et al.* (2007) found that a Telone II and chloropicrin combination with metham potassium might offer a viable substitute for MBr for Georgia pepper producers. Ferrer *et al.* (2010) analyzed the profitability of MBr and its alternatives in Georgia pepper production and showed that a combination of 1,3-dichloropropene plus chloropicrin, metham sodium,

---

[1] Between 2005 and 2013, critical use exemptions (CUEs) were authorized in Florida for commercial tomato production; however, the permitted exemptions were not able to influence the state's tomato production. After they expired, an exemption petition was submitted in 2013 but was rejected.
[2] Mexico accounted for 90% of total US tomato imports in recent years, replacing Florida as the dominant supplier in the US market. Canada, as a developed country, had the same MBr phase-out schedule as the US, but represented only 9% of total US tomato imports.

and smooth low density black on black polyethylene mulch was the most profitable fumigant and mulch option. Similarly, Fonash *et al.* (2010) concluded that 1,3-dichloropropene plus chloropicrin and metham sodium could maximize pepper production. Sydorovych *et al.* (2008) investigated the cost-effectiveness of MBr and its alternatives used in tomato production in North Carolina. The authors compared MBr with Telone-C35, Telone II, Chloropicrin, Midas, Inline, and others and found *feasible* alternatives to MBr for tomato production in the state. However, the authors did not consider price variations (using only one set of prices) and the potential impact on the economic outcome, nor did they account for the risk associated with treatment effects. In this study, in addition to partial budgeting, sensitivity analysis as well as certainty equivalent analysis was further conducted to ensure robustness of findings.

2. Materials and methods

2.1 Partial budgeting analysis

Partial budgeting analysis is a standard technique to assess the economic impact of a change in a farm system (Kay *et al.*, 2016). It is frequently used to estimate the impact of various alternative production techniques when the changes involve only part of the production system (Roberts and Swinton, 1996; Warmann, 1995; Wossink and Osmond, 2002). The partial budgeting approach sums up the negative effects of a new treatment (relative to a base or standard treatment) and its positive effects (Sydorovych *et al.*, 2008) to assess the net effect of the treatment. Negative effects consist of added costs and reduced returns of the alternative treatment, while positive effects include reduced costs and added returns of the treatment. In the case of this study, average yields, fumigation costs, and harvest and marketing costs that change with fumigation treatments are considered in the calculation of net effects. Those costs, such as land rent and asset depreciation, that are fixed across treatments are not considered in partial budgeting analysis. In this analysis, the base treatment is MBr:Pic (67:33) (a formulated mixture of 67% MBr and 33% chloropicrin), a popular MBr formula used by tomato growers in Florida before the MBr ban.

2.2 Whole farm budgeting analysis

The whole farm budgeting analysis summarizes the financial information of the entire farm business (Riggs *et al.*, 2005). The interest is on the level of economic performance (e.g. profit) of the entire operation after treatment, not just the changes caused by treatments, to assess whether a treatment would make the operation economically sustainable. Besides revenue, it estimates all the costs incurred in tomato production. The cost budget accounts for all expense categories to estimate the total cost of production per acre. In this analysis, fumigation costs, harvest & marketing costs, and other production costs (e.g. fixed costs) are analyzed to estimate the total cost of tomato production in Florida. Combining the total revenue and total cost information, the average net profit per acre ($\bar{\pi}$) of each fumigation treatment is estimated.

2.3 Certainty equivalent analysis

The above budgeting analyses focus only on the mean value of the net effect (or net profit) of each treatment, ignoring the variation of the net profit across replications for each treatment. When volatility (risk) is a concern, 'optimal' pest management options sometimes differ across growers, depending on their risk attitudes. For example, some growers may prefer a treatment that brings slightly less profit on average but is more stable. In this study, we further conduct certainty equivalent analysis that incorporates both the mean and the variation (distribution) in treatment effects into the expected utility model to determine the optimal options. Specifically, the certainty equivalent (CE) is defined as the amount of a risk-free payoff to which a decision maker would be indifferent when compared with a risky choice (Hardaker *et al.*, 2004; Moss, 2010) such as the treatment effect with variations in this study. The CE method accounts for three aspects of each treatment. The first is the average fumigation treatment effect, namely the expected money value (EMV) of profit using the treatment. The second is the risk or volatility of the treatment effect, represented by the distribution of the profit. The more volatile the profit, the less the CE value is. The third is the degree of risk

aversion of the grower, as the same risky outcome may represent a lower level of welfare or satisfaction to a more risk-averse grower than it does for a less risk-averse one. That is, some growers may discount the risky outcome more than others because of different risk attitudes. The degree of risk aversion is captured by the curvature of the utility function, and the key economic factor affecting risk aversion is the wealth of growers (Hardaker *et al.*, 2004). It is generally believed that a poorer economic agent is more concerned of risk than a wealthy one.

The negative exponential utility function is often used in risk analyses (Babcock *et al.*, 1993; Hardaker *et al.*, 2004). However, the assumption of constant absolute risk aversion (CARA) of this function implies that the risk attitude of an economic agent does not change with his wealth, which is a restrictive, strong assumption. In this study, we allow the absolute risk aversion (ARA) to vary with wealth and use the more plausible, power utility function to evaluate the MBr alternatives. The power utility function implies decreasing absolute risk aversion (DARA) and constant relative risk aversion (CRRA). A large body of literature has found evidence of DARA, which has become a sound assumption in the literature (Saha, 1993). Although there is little consensus on the nature of relative risk aversion, some empirical findings have supported CRRA (Chiappori and Paiella, 2011).[3]

The power utility function takes the following form:

$$U(W) = \begin{cases} \frac{W^{1-r}}{1-r} & if\ r > 0, r \neq 1 \\ Ln(W) & if\ r = 1 \end{cases} \tag{1}$$

Where W is the ending wealth, and r is the relative risk-aversion coefficient (RRAC). The range of r is set from 1 to 4, representing 'normal risk aversion' to 'extreme risk aversion' (Anderson and Dillon, 1992). Specifically, the formula for calculating the CE of a specific treatment with the power utility function is (Clemen, 1991):

$$E(U) = \sum_i \frac{p_i(\omega+\pi_i)^{(1-r)}}{1-r} \tag{2}$$

$$CE = [E(U)(1-r)]^{\frac{1}{1-r}} - \omega \tag{3}$$

Where $E(U)$ is the expected utility, ω is the initial wealth, π_i is the risk outcome i (net profit) of the treatment, $\omega + \pi_i = W_i$. p_i is the probability of π_i, and CE is the certainty equivalent of the treatment. π_i is randomly drawn from a distribution derived based on the empirical distribution of trial replicates using the Simetar program (Richardson, 2008).

As demonstrated above, fumigation treatment affects profit and therefore the wealth at the end of the season. In this case, to calculate the CE value of each fumigation treatment, a representative farm is assumed, representing a tomato farm in Florida with an average farm equity and farm size. The farm equity is regarded as the initial wealth ω of the farm. According to the Census of Agriculture conducted by the National Agricultural Statistics Service of the United States Department of Agriculture (USDA/NASS, 2013), the average tomato farm size in Florida is about 70 acres. Based on the published farm financial data from the Agricultural Resource Management Survey (ARMS) of the United States Department of Agriculture (USDA/ARMS, 2013), the average farm equity of vegetable farms in Florida is about $3,420,056. Therefore, the representative farm analyzed is a tomato farm in Florida with 70 acres of land and $3,420,056 in farm equity.

---

[3] Wakker (2008) warned that the power utility function exhibits an extreme behavior when *w*=0, causing empirical and analytical problems. However, this will not happen here, as *w* is always far away from zero in our study.

2.4 Data description

Yield and input use data were collected from field trials conducted by the University of Florida in fall 2013. Fumigant treatments included two MBr formulations, MBr:Pic (67:33) and MBr:Pic (50:50); three alternative fumigant treatments, TE-3 (a formulated mixture of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide), PicChlor 60 (a formulated mixture of 1,3-dichloropropene and chloropicrin), and FL-3 way (consisting of separate applications of 1,3-dichloropropene (Telone II), chloropicrin (Pic100), and metam potassium (K-Pam 54)); and a non-fumigated control treatment.[4] There were four fields, and each field had four replicate blocks. Each block had three beds divided into six plots, and each plot was 2.67 feet wide by 75 feet long (200 square feet = 0.0046 treated acre). Six treatments were applied on the six plots, respectively, in each block.

The four fields had different levels of weed and nematode populations in order to test the efficacy of MBr and alternative fumigants. Fumigation costs consisted of costs for materials, machinery, and labor. For fumigant material costs, the market prices of MBr:Pic (67:33) and MBr:Pic (50:50) used in the field trials were $12.00/lb and $8.00/lb, respectively, which were much higher than other fumigant prices. This was because restrictions on MBr production, import, and consumption under the Montreal Protocol have driven the market price of MBr up in the US in recent years. For a fair and robust analysis, the original price of MBr before the ban in 1997 was used and adjusted up for inflation.[5] In addition, virtually impermeable film (VIF) mulch and drip tape costs were also incorporated into the fumigation material costs, estimated at $448/acre and $150/acre, respectively.

Fumigation machinery costs only included fuel and lubricant costs. Depreciation and other non-cash overhead were assumed to remain unchanged across treatments and therefore were excluded from the partial budgeting analysis. For each treatment, per plot tractor time was recorded and fuel costs were estimated accordingly.[6] Lubricant cost was assumed as 10% of the fuel cost, as suggested by Stoddard *et al.* (2007).

For the fumigation labor costs, it was assumed that the fumigation operation required one tractor driver and three field workers to lay VIF mulch and drip tapes. Labor time for the tractor driver was set to be 20% higher than the average operation time to account for the extra labor for activities such as equipment setting up, moving, maintenance, and field repair. After calculating the average labor operation time for each fumigation treatment, the labor costs were estimated by multiplying the wage rate by the average labor hours.[7]

Harvest and marketing costs included picking/packing/hauling cost, container cost, selling cost, and organization fee. Using 'Estimated tomato production costs in the Manatee/Ruskin area' published by the University of Florida in 2009 as the reference (UF/IATPC, 2009), the harvest and marketing costs in this study were estimated at $3.51/carton after adjusted for inflation (each carton contained 25 lbs of tomatoes).[8] Except for fumigation costs and harvest and marketing costs, other cost items in this reference were indexed to 2013, adjusted for inflation.

---

[4] The application rates of each fumigation treatment for the four fields were as follows: 350 lbs/acre of MBr:Pic (67:33), 350 lbs/acre of MBr:Pic (50:50), 400 lbs/acre of TE-3, 300 lbs/acre of PicChlor 60, and FL-3 way (122 lbs/acre of Telone II, 150 lbs/acre of Pic100, and 60 gals/acre of K-Pam 54). All treatments were covered with virtually impermeable film (VIF) mulch, and applied with the same amount of fertilizers and fungicides; drip tape irrigation was also applied to each field during the growing season.

[5] According to production budget statistics from the FFVA, the price of MBr in 1997 in Florida tomato production areas was about $3.01/lb. After being adjusted with the Producer Price Index released by the United States Bureau of Labor Statistics, the MBr price in 2013 was set at $5.45/lb (USBLS, 2014). Accordingly, the MBr:Pic (67:33) and MBr:Pic (50:50) prices were adjusted to $4.80/lb and $4.46/lb, respectively.

[6] According to the tractor fuel consumption information from the test reports published by the Nebraska Tractor Test Laboratory, the fuel cost was estimated by multiplying the average tractor time by the per hour fuel consumption based on standard power takeoff (PTO) horsepower.

[7] Based on the farm labor rate information released by the National Agricultural Statistics Service of the United States Department of Agriculture (USDA/NASS, 2013), the hourly wage rates during the July 2013 reference week were $12.55 for all hired workers and $10.70 for field workers.

[8] The estimated costs in this reference were structured as 'pre-harvest cost' and 'harvest and marketing costs'. The pre-harvest cost included (1) operating costs, which covered major variable cost items such as fertilizer, fumigants, herbicides, (2) miscellaneous, which included minor variable cost items such as scouting and stakes, (3) fixed costs, including land rent, machinery fixed cost, and farm management and overhead.

Tomato market prices used in the analysis were from the Agricultural Marketing Service of the United States Department of Agriculture (USDA/AMS, 2013). The following average prices of fresh tomatoes in southwest Florida in 2013 were used in the analysis: $12.65/carton for jumbo and extra-large tomatoes, $11.21/carton for large tomatoes, and $10.50/carton for medium and small tomatoes. Prices in other years will also be used in sensitivity analysis. The net profit was calculated using gross revenue minus fumigation costs, harvest and marketing costs, and other costs. For comparison purpose, gross profit was also calculated, using gross revenue minus fumigation costs, harvest and marketing costs, and other variable costs, excluding fixed costs.

3. Results

3.1 Partial budgeting analysis results

Table 1 presents the costs of fumigation with MBr:Pic (67:33) and its alternative treatments. The fumigation costs are separated into material costs, labor costs, and machinery costs. The projected fumigation costs of the base treatment, MBr:Pic (67:33), are the most expensive, estimated at $2398.18/acre. Excluding the non-fumigated treatment, the most cost-saving fumigation treatment is PicChlor 60, which saves $815/acre. This is followed by TE-3, FL-3 way, and MBr:Pic (50:50), with savings of $380, $185, and $119 per acre, respectively.

The average tomato yields of MBr:Pic (67:33) and the alternative treatments are shown in Table 2. The results show that MBr:Pic (67:33) produces the highest average marketable yield (31,402 lbs/acre), followed by MBr:Pic (50:50) (29,564 lbs/acre), TE-3 (27,689 lbs/acre), PicChlor 60 (23,583 lbs/acre), FL-3 way (21,334 lbs/acre), and the non-fumigated treatment (18,115 lbs/acre). This is expected given that these alternatives lack the broad-spectrum pest control effect.

Per acre gross revenues are estimated using tomato market prices and average yields graded in different fruit size categories. The base treatment, MBr:Pic (67:33), leads to the highest average gross revenue at $14,484.39/acre. TE-3 performs the best among the alternative treatments that exclude MBr. PicChlor 60, currently the most fumigant used in Florida tomato production and considered the new industry standard in post-MBr production, incurs a loss of $3,568.52/acre in gross revenue relative to MBr:Pic (67:33). FL-3 way results in even more losses in gross revenue ($4,402.54/acre) relative to MBr:Pic (67:33), followed by the non-fumigated treatment ($6,175.20/acre).

Table 3 displays the negative and positive effects of each fumigation treatment relative to the base treatment, calculated with the estimated fumigation costs (Table 1), and gross revenues (Table 2). Table 3 shows that

Table 1. Average tomato fumigation costs.[1,2]

MBr and alternative treatments	Fumigation labor costs ($/acre)	Fumigation machinery costs ($/acre)	Fumigation material costs ($/acre)	Total fumigation costs ($/acre)	Fumigation costs relative to MBr:Pic (67:33) ($/acre)
Non-fumigated	69.40	50.78	598.00	718.18	-1,680.00
MBr:Pic (67:33)	69.40	50.78	2,278.00	2,398.18	0.00
MBr:Pic (50:50)	69.40	50.78	2,159.00	2,279.18	-119.00
TE-3	69.40	50.78	1,898.00	2,018.18	-380.00
PicChlor 60	69.40	50.78	1,463.00	1,583.18	-815.00
FL-3 way	92.99	106.95	2,012.70	2,212.64	-185.54

[1] The fumigation machinery costs only included diesel and lubricant costs; depreciation and other non-cash overhead were excluded.
[2] MBr: methyl bromide, MBr:Pic: formulated mixture of MBr and chloropicrin, TE-3: formulated mixture of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide, PicChlor 60: formulated mixture of 1,3-dichloropropene and chloropicrin, FL-3 way: consisting of separate applications of 1,3-dichloropropene (Telone II), chloropicrin (Pic100), and metam potassium (K-Pam 54)).

Table 2. Marketable tomato yields and gross revenues for the 2013/14 season.[1,2]

MBr and selected alternative treatment	Jumbo and extra-large tomato (lbs/acre)	Large tomato (lbs/acre)	Medium and small tomato (lbs/acre)	Total yield (lbs/acre)	Gross revenue ($/acre)	Gross revenues relative to MBr:Pic (67:33) ($/acre)
Non-fumigated	6,633.15	4,605.98	6,875.00	18,115.49	8,309.20	-6,175.20
MBr:Pic (67:33)	12,759.51	6,977.58	11,665.08	31,402.17	14,484.39	0.00
MBr:Pic (50:50)	11,872.28	6,694.97	10,996.60	29,563.86	13,627.97	-856.42
TE-3	10,855.30	6,095.11	10,738.45	27,688.86	12,735.98	-1,748.42
PicChlor 60	9,974.86	5,395.38	8,212.64	23,582.88	10,915.88	-3,568.52
FL-3 way	11,502.72	4,656.25	5,175.27	21,334.24	10,081.85	-4,402.54

[1] Tomato marketing prices were $12.65/carton for jumbo and extra-large tomatoes, $11.21/carton for large tomatoes, and $10.50/carton for medium and small tomatoes (each carton contains approximately 25 lb of tomatoes).

[2] MBr: methyl bromide, MBr:Pic: formulated mixture of MBr and chloropicrin, TE-3: formulated mixture of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide, PicChlor 60: formulated mixture of 1,3-dichloropropene and chloropicrin, FL-3 way: consisting of separate applications of 1,3-dichloropropene (Telone II), chloropicrin (Pic100), and metam potassium (K-Pam 54)).

Table 3. Net economic effects of treatments relative to MBr:Pic (67:33).[1]

MBr:Pic (67:33) and its alternatives	Added costs of the alternative treatment ($/acre)	Reduced returns of the alternative treatment ($/acre)	Total negative effects of the alternative treatment ($/acre)	Reduced costs of the alternative treatment ($/acre)	Added returns of the alternative treatment ($/acre)	Total positive effects of the alternative treatment ($/acre)	Total effects relative to MBr:Pic (67:33) ($/acre)
Non-fumigated	0	6,175.20	6,175.20	3,545.45	0	3,545.45	-2,629.75
MBr:Pic (67:33)	0	0	0	0	0	0	0
MBr:Pic (50:50)	0	856.42	856.42	377.10	0	377.10	-479.32
TE-3	0	1,748.42	1,748.42	901.35	0	901.35	-847.07
PicChlor 60	0	3,568.52	3,568.52	1,912.83	0	1,912.83	-1,655.69
FL-3 way	0	4,402.54	4,402.54	1,599.08	0	1,599.08	-2,803.46

[1] MBr: methyl bromide, MBr:Pic: formulated mixture of MBr and chloropicrin, TE-3: formulated mixture of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide, PicChlor 60: formulated mixture of 1,3-dichloropropene and chloropicrin, FL-3 way: consisting of separate applications of 1,3-dichloropropene (Telone II), chloropicrin (Pic100), and metam potassium (K-Pam 54)).

all the alternatives lead to negative total net effects relative to MBr:Pic (67:33); FL-3 way has the largest negative net effect of –$2,803.46/acre due to its high fumigation costs and poor yield performance, followed by the non-fumigated treatment (–$2,629.75/acre), PicChlor 60 (–$1,655.69/acre), TE-3 (–$847.07/acre), and MBr:Pic (50:50) (–$479.32 /acre). It can be concluded that, although fumigation costs of the MBr:Pic (67:33) treatment are higher than other treatments, its outstanding yield performance makes it the most cost-effective treatment. Among non-MBr treatments, TE-3 performs the best. Results indicate that switching from MBr:Pic (67:33) to the new industry standard, PicChlor 60, results in a loss of –$3,568.52/acre in farm revenue (sales) and –$1,655.69/acre in profit (net treatment effect).

The above results are calculated based on the marketing year of the 2013/14 season. To examine the effect of market conditions on the outcome, we conducted a sensitivity analysis. The prices of the 2014/15, 2015/16, and 2016/17 seasons were used. For example, the price of jumbo & extra-large tomatoes was $13.76/carton, $17.11/carton, and $10.82/carton, representing increases of 9% and 35% and a decline of 15%, respectively,

compared to the 2013/14 base season. These three marketing years, which represent average, high, and low scenarios, are used to examine the sensitivity of the ranking to market conditions. Table 4 shows the total negative and positive effects of the MBr alternatives relative to MBr:Pic (67:33). The results show that MBr:Pic (67:33) still performs the best in terms of cost effectiveness under different prices. Compared to 2013/2014, the total *net* effects relative to MBr:Pic (67:33) increase with market prices in 2014/2015 and 2015/2016, indicating that higher prices make MBr:Pic (67:33) more cost effective. Although the price decline in 2016/2017 narrows the total *net* effect gap between MBr:Pic (67:33) and its alternatives, MBr:Pic (67:33) still outperforms the others. Therefore, the ranking of fumigation alternatives is insensitive to market conditions.

3.2 Whole farm budgeting analysis results

The whole farm budgeting results show that all treatments result in negative net profit. Net profit is defined as sales minus all costs, including fixed costs and other costs. Fixed costs are defined as land rent, asset depreciation, and overhead in this study. According to Table 5, base treatment MBr:Pic (67:33) leads to a net profit of -$2,486.95/acre, followed by MBr:Pic (50:50) (-$2,966.27/acre), TE-3 (-$3,334.02/acre), PicChlor 60 (-$4,142.64/acre), the non-fumigated treatment (-$5,116.70/acre), and FL-3 way (-$5,290.41/acre). The net profit results suggest that the current production and market situation is creating tremendous challenges

Table 4. Sensitivity analysis of net economic effects of treatments relative to MBr:Pic (67:33).[1,2]

	Total negative effects of the alternative treatment ($/acre)	Total positive effects of the alternative treatment ($/acre)	Total effects relative to MBr ($/acre)
2014/2015 Season			
Non-fumigated	6,883.12	3,545.64	-3,337.48
MBr:Pic (67:33)	0.00	0.00	0.00
MBr:Pic (50:50)	953.95	377.06	-576.90
TE-3	1,944.51	901.31	-1,043.20
PicChlor 60	3,998.42	1,912.79	-2,085.63
FL-3 way	4,993.13	1,599.09	-3,394.04
2015/2016 Season			
Non-fumigated	8,627.18	3,545.64	-5,081.55
MBr:Pic (67:33)	0.00	0.00	0.00
MBr:Pic (50:50)	1,194.73	377.06	-817.67
TE-3	2,439.97	901.31	-1,538.67
PicChlor 60	5,018.46	1,912.79	-3,105.68
FL-3 way	6,282.71	1,599.09	-4,683.63
2016/2017 Season			
Non-fumigated	5,375.71	3,545.64	-1,830.08
MBr:Pic (67:33)	0.00	0.00	0.00
MBr:Pic (50:50)	745.03	377.06	-367.97
TE-3	1,521.73	901.31	-620.43
PicChlor 60	3,117.69	1,912.79	-1,204.90
FL-3 way	3,876.92	1,599.09	-2,277.83

[1] Prices for jumbo and extra-large tomatoes, large tomatoes, and medium and small tomatoes were $13.76, $12.77, and $12.00 per carton, respectively, in the 2014/15 season; were $17.11, $16.40, and $15.02 per carton, respectively, in 2015/16; were $10.82, $10.03, and $9.25 per carton, respectively, in 2016/17; and were $12.65, $11.21, and $10.50 per carton, respectively, in 2013/14.
[2] MBr: methyl bromide, MBr:Pic: formulated mixture of MBr and chloropicrin, TE-3: formulated mixture of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide, PicChlor 60: formulated mixture of 1,3-dichloropropene and chloropicrin, FL-3 way: consisting of separate applications of 1,3-dichloropropene (Telone II), chloropicrin (Pic100), and metam potassium (K-Pam 54)).

Table 5. Average costs and gross and net profits.[1,2]

MBr and selected alternative treatments	Fumigation cost ($/acre)	Harvest & marketing cost ($/acre)	Total costs ($/acre)	Gross profit ($/acre)	Net profit '$\overline{\pi}_i$' ($/acre)	Profit relative to MBr:Pic (67:33) ($/acre)	Break-even grower price ($/carton)
Non-fumigated	718.18	2,543.41	13,425.89	-914.35	-5,116.70	-2,629.75	18.53
MBr:Pic (67:33)	2,398.18	4,408.87	16,971.34	1,715.39	-2,486.95	0.0	13.51
MBr:Pic (50:50)	2,279.18	4,150.77	16,594.24	1,236.07	-2,966.27	-479.32	14.03
TE-3	2,018.18	3,887.52	16,069.99	868.33	-3,334.02	-847.07	14.51
PicChlor 60	1,583.18	3,311.04	15,058.51	59.71	-4,142.64	-1,655.69	15.96
FL-3 way	2,212.64	2,995.33	15,372.26	-1,088.07	-5,290.41	-2,803.46	18.01

[1] Other than fumigation cost and harvest & marketing cost, other production costs for each treatment are estimated at $10,164.30/ acre, of which the fixed costs are estimated at $4,202.34/acre.

[2] MBr: methyl bromide, MBr:Pic: formulated mixture of MBr and chloropicrin, TE-3: formulated mixture of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide, PicChlor 60: formulated mixture of 1,3-dichloropropene and chloropicrin, FL-3 way: consisting of separate applications of 1,3-dichloropropene (Telone II), chloropicrin (Pic100), and metam potassium (K-Pam 54)).

for the industry. Excluding the fixed costs in the calculation, the gross profits present a less severe situation. Except for the non-fumigated treatment and FL-3 way, all other treatments generate positive gross profits. This implies that the current market can sustain short-term farm business operations with the alternative fumigants, but it will still cause financial stress in the long run.

Table 5 also indicates the average 'breakeven' grower prices required to cover the total fresh tomato production costs. The yield and cost differences among treatments result in different prices required to make the business break even (i.e. to earn a zero net profit). For example, in a market with an average price of $15.96/carton, PicChlor 60 would result in zero net profit. Note that an average price of $15.96/carton is approximately 40% higher than the average price in fall 2013 during this experiment; to have such a high price is highly unlikely in a normal year. However, this unusually good situation did occur in winter of 2015 because of multiple storms in Mexico and adverse weather conditions in other production areas in the US, giving Florida growers unexpected but much needed windfalls.

3.3 Certainty equivalent results

The CE results are plotted across relative risk aversion coefficient (RRAC) values (from 1 to 4) by treatment in Figure 1. In addition, the CE values of each treatment are extended in dashed lines to reach the vertical CE axis. At the point where the RRAC equals zero (i.e. if growers are 'risk neutral' or do not care about risk), the corresponding CE value of each treatment is the EMV of its profit for 70 acres, calculated using the average treatment effect in the whole farm budgeting analysis.

The ranking results illustrate that MBr:Pic (67:33) is still the most cost-effective treatment in terms of the CE after accounting for risk and growers' risk aversion, and it is followed by MBr:Pic (50:50), TE-3, PicChlor 60, FL-3 way, and the non-fumigated treatment. For a grower with a 'normal' risk aversion (RRAC=1), an average 70-acre farm would have a CE of -$191,874 under MBr:Pic (67:33). When risk and growers' risk attitude are not considered (RRAC=0), average net profit would be -$174,087. The new industry standard, PicChlor 60, produces a CE of -$305,040 for a grower with 'normal' risk aversion, while its average net profit is -$289,985. Both numbers suggest serious challenges for the industry.

It is worth noting that FL-3 way and the non-fumigated treatment intersect approximately at RRAC=1.30; after that, as risk aversion (RRAC) further increases, FL-3 way becomes a better choice than the non-fumigated
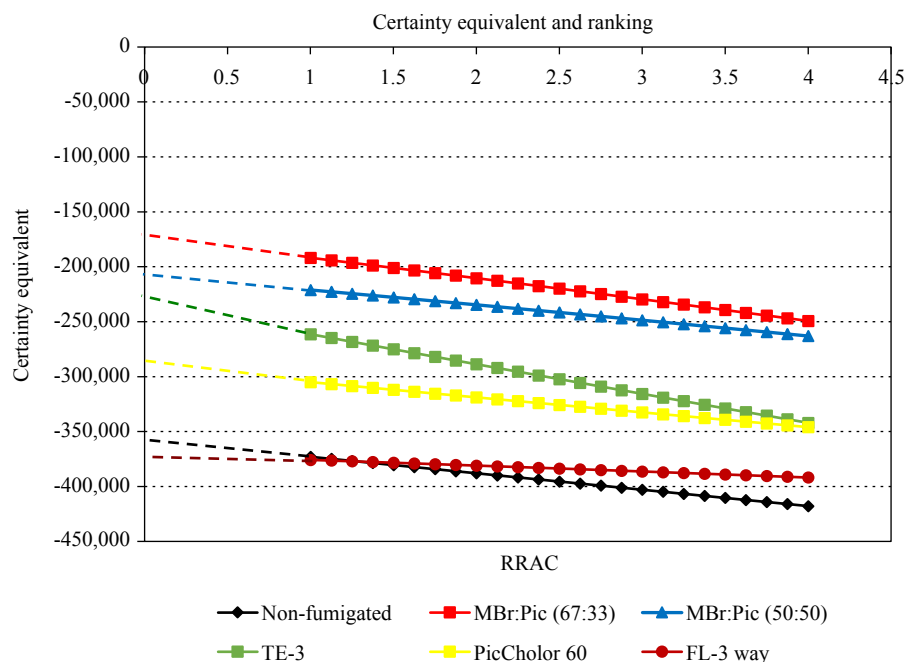
Figure 1. Certainty equivalent values of treatments' profits for a farm of 70 acres.

treatment. This is because non-fumigated operation has a much higher volatility, while FL-3 way produces relatively stable results; growers who are more risk averse would prefer FL-3 despite it having a slightly lower average. Among all the alternatives, TE-3 produces the most volatile results, but it is still the best among non-MBr treatments as its higher average profit overcompensates the risk discount. However, if a grower is extremely risk averse (RRAC=4), PicChlor 60 is almost as good as TE-3.

In Florida, there are many small tomato farms smaller than 70 acres, which bring down the average farm size. However, most tomato acreage is concentrated in a small portion of large farms. For these large farms, the total loss would be larger.

4. Discussions and conclusions

MBr has been proven to be the optimal soil fumigant because of its reliability and effectiveness but it is being phased out under the Montreal Protocol. Research has been conducted to discover the technical efficacy of alternative fumigants under different environmental conditions, but robust economic analysis is lacking. This study aims to fill this gap and provides an *ex post* economic impact analysis of the MBr phase-out for tomato production in Florida. A sensitivity analysis is conducted to account for the effect of different prices on the outcome while yield risks are further considered in the stochastically simulated yields (hence profits) that are used to construct the certainty equivalent measures in this research.

The budgeting and risk analysis results indicate that MBr:Pic (67:33) performs the best in terms of cost effectiveness compared to MBr:Pic (50:50) and other alternative fumigants, while TE-3 performs the best among non-MBr treatments. Compared with MBr:Pic (67:33), PicChlor 60, the current standard fumigant for the Florida tomato industry, reduced the average gross revenue by $3,569/acre and profit by $1,656/acre. This has created further challenges for the industry as it was already struggling with Mexican competition and depressed prices, which has attracted considerable attention in recent literature (Suh *et al.*, 2017; Wu *et al.*, 2018). Sensitivity analyses under different price scenarios suggest that the performance ranking of alternative fumigation systems does not change although the numerical results vary. The analysis reveals that TE-3 is more effective than the current industry standard and should be promoted instead in commercial production.

In summary, our results suggest that no alternative fumigant systems currently available can substitute MBr cost-effectively from an economic perspective. Fumigation costs of MBr:Pic (67:33) treatment are higher than other treatments studied, but its outstanding yield performance makes it most cost effective. The current industry standard PicChlor 60, is economically less effective, and MBr phase-out is causing significant losses in yields, gross revenue, and profits.

Note that the base treatment used in this study is MBr:Pic (67:33). According to the tomato grower survey conducted by the Florida Fruit and Vegetable Association, Florida tomato growers used to apply fumigant with a higher concentration of MBr as well, such as MBr:Pic (98:2). Due to the availability problem, the field trials only applied MBr:Pic (67:33) and MBr:Pic (50:50). However, it can be assumed that if MBr:Pic (98:2) had been applied, the gap of gross revenue and profits between PicChlor 60 and MBr:Pic (98:2) would be even larger, as research has repeatedly shown that fumigant mixes with a higher concentration of MBr is more effective in pest control. It should also be noted that this study did not analyze other factors that could cause losses in farm production due to the MBr phase-out, such as reduced (or given up) double-cropping because of increased pest pressure. This study did not account for the effects of pest pressure build-up over time either, which the industry has reported due to the lower efficacy of alternatives, and this pressure is causing significant losses of crops. Considering all of these factors, the above estimates only represent the lower bound of losses caused by the phase-out of MBr, and the comprehensive losses would be higher. The large losses from MBr phase-out shown in this study suggest that potential impacts of future pest management policies should be carefully assessed before they are implemented to mitigate risk and avoid large technological shocks to the industry.

References

Anderson, J.R. and J.L. Dillon. 1992. *Risk analysis in dry land farming systems (No. 2)*. Food & Agriculture Organization of the United Nations. The World Bank, Washington D.C., USA.

Babcock, B.A., E.K. Choi and E. Feinerman. 1993. Risk and probability premiums for CARA utility functions. *Journal of Agricultural & Resource Economics* 18 (1): 17-24.

Byrd, M.M., C.L. Escalante, E.G. Fonsah and M.E. Wetzstein. 2007. Feasible fumigant-herbicide system alternatives to methyl bromide for bell pepper producers. *Journal of Agribusiness* 25 (1): 31-45.

Clemen, R.T. 1991. *Making hard decisions*. PWS-Kent Publishing, Boston, MA, USA.

Chiappori, P. and M. Paiella. 2011. Relative risk aversion is constant: evidence from panel data. *Journal of the European Economic Association* 9 (6): 1021-1052.

Guan, Z., F. Wu, F. Roka and A. Whidden. 2015. Agricultural labor and immigration reform. *Choices* 30 (4), 1-9.

Ferrer, M.C.R., E.G. Fonsah, C.L. Escalante and S. Culpepper. 2010. Profitability efficiency analysis of methyl bromide fumigants and mulch systems alternatives for pepper production in Georgia. Paper presented at Southern Agricultural Economics Association Conference, Orlando, 6-9 February 2010.

Fonsah, E., Y. Yu, C. Escalante, S. Culpepper and X. Deng. 2010. Comparative yield efficiencies of methyl bromide substitute fumigants and mulching systems for pepper production in the Southeast. *Journal of Agribusiness and Rural Development* 1 (15): 55-65.

Hardaker, J.B., R.B.M. Huirne, J.R. Anderson and G. Lien. 2004. *Coping with Risk in Agriculture*. CABI Publishing, Oxfordshire, UK.

Kay, R.D., W.M. Edwards and P.A. Duffy. 2016. *Farm management*. McGraw-Hill, New York, NY, USA.

Moss, C.B. 2010. *Risk, Uncertainty, and the Agricultural Firm*. World Scientific Publishing Co. Pte. Ltd., Hackensack, NJ, USA.

Osteen, C.D. 2000. *Economic implications of the methyl bromide phaseout*. United States Department of Agriculture Economic Research Service, February. Available at: https://www.ers.usda.gov/publications/pub-details/?pubid=42290.

Richardson, J.W. 2008. *Simulation for applied risk management with an introduction to SIMETAR*. Department of Agricultural Economics, Texas A&M University, College Station, Texas, TX, USA.

Riggs, W.W., K.R. Curtis and T.R. Harris. 2005. *Importance & use of enterprise budgets in agricultural operations*. University of Nevada Cooperative Extension, University of Nevada, Reno, Special Publication 5-12. Available at http://www.unce.unr.edu/publications/files/ag/2005/sp0512.pdf.

Roberts, W.S. and S.M. Swinton. 1996. Economic methods for comparing alternative crop production systems: a review of the literature. *American Journal of Alternative Agriculture* 11 (1): 10-17.

Roka, F.M. and Z. Guan. 2018. Farm labor management trends in Florida, USA – challenges and opportunities. *International Journal of Agricultural Management* 7 (1), 1-9.

Stoddard, C.S., M. LeStrange, B. Aegerta, K. Klonsky and R. De Moura. 2007. *Sample costs to produce fresh market tomatoes*. University of California Cooperative Extension, University of California, Davis, Publication No. TM-SJ-07. Available at: https://tinyurl.com/y28x5s6x.

Saha, 1993. Expo-power utility: a 'flexible' form for absolute and relative risk aversion. *American Journal of Agricultural Economics* 75 (4): 905-913.

Suh, D.H., Z. Guan, and H. Khachatryan. 2017. The impact of Mexican competition on the U.S. strawberry industry. *International Food and Agribusiness Management Review* 20 (4): 591-604.

Sydorovych, O., C.D. Safley, R.M. Welker, L.M. Ferguson, D.W. Monks, K. Jennings, J. Driver and F.J. Louws. 2008. Economic evaluation of methyl bromide alternatives for the production of tomato in North Carolina. *Horttechnology* 18 (4): 705-713.

University of Florida International Agricultural Trade and Policy Center (UF/IATPC). 2009. *Fall tomatoes: estimated production costs in the Manatee/Ruskin area, 2008-2009*. Available at: https://fred.ifas.ufl.edu/pdf/iatpc/files/RuskinFallTomato09.pdf.

United States Bureau of Statistics (USBLS). 2014. *Producer price index industry data*. United States Bureau of Statistics, Washington, D.C., USA. Available at: http://www.bls.gov/ppi/.

United States Department of Agriculture, Agricultural Resource Management Survey (USDA/ARMS). 2013. *ARMS farm financial and crop production practices*. United States Department of Agriculture, Agricultural Resource Management Survey, Washington, D.C., USA. Available at: https://tinyurl.com/yyo44jvu.

United States Department of Agriculture, National Agricultural Statistics Service (USDA/NASS). 2013. *Census of agriculture*. United States Department of Agriculture, National Agricultural Statistics Service, Agricultural Statistics Board, Washington, D.C., USA. Available at: https://tinyurl.com/yxh4yjzm.

VanSickle, J.J., C. Brewster and T.H. Spreen. 2000. *Impact of a methyl bromide ban on the US vegetable industry*. Institute of Food and Agricultural Sciences Extension, University of Florida, UF/IFAS Bulletin No. 333.

Wakker, P. 2008. Explaining the characteristics of the power (CRRA) utility family. *Health Economics* 17: 1329–1344.

Warmann, G. W. 1995. *Economics of liming Kansas cropland*. Agricultural Experiment Station and Cooperative Extension Service, Kansas State University, Publication No. MF-2137. Available at: http://www.ksre.ksu.edu/bookstore/pubs/MF2137.pdf.

Wossink, G.A.A. and D.L. Osmond. 2002. Farm economics to support the design of cost-effective best management practice (BMP) programs to improve water quality: nitrogen control in the Neuse River Basin, North Carolina. *Journal of Soil and Water Conservation* 57 (4): 213-220.

Wu, F., Z. Guan, and D. Suh. 2018. The effects of tomato suspension agreements on market price dynamics and farm revenue. *Applied Economic Perspectives and Policy* 40 (2): 316-332