Alternative management practices to reduce soil fumigant use in key California crops: A meta-analytic approach

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The fumigant dilemma

- Effective control of pathogens, nematodes & weeds
- Maintain high yields in strawberry, tomato, etc.
- But MeBr is ozone depleting substance
  - Global phase-out began in 1990s
  - Replaced by 4 alternative fumigants in CA

Source: PUR database
Spatial & crop distribution of fumigant use in CA

Total fumigant use at township (6 mi. x 6 mi.) level

California’s top fumigant use crops by lbs. (avg. 2008-12)

- Strawberries (26.6%)
- Carrots (16.3%)
- Tomatoes (10.6%)
- Potatoes (4.2%)
- Grapes (3.0%)
- Almonds (2.7%)
- Walnuts (1.6%)

Source: PUR Database
Issues with the four alternative fumigants

Toxicity

- 1,3-dichloropropene a “probable carcinogen” (US EPA)
- Chloropicrin & metam symptoms similar to pepper spray

All are volatile organic compounds (VOCs) used at 100s of lbs/acre

Increasing use restrictions in CA

- Buffer zones for difficult-to-evacuate sites (e.g., hospitals)
- Township caps in some southern CA areas
- MeBr use exemptions in strawberries may not last forever

The 4 alternative fumigants have similar issues worldwide

Global research effort on ways to reduce use of all fumigants
Alternative management practices

Global research effort has focused on several practices:

Soil solarization/ biofumigation
Anaerobic soil disinfestation (ASD)
Non-fumigant chemicals
Grafting/resistant varieties

Soil-less culture
Crop rotation (host/non-host)
Steam or heat treatment
Biological control agents
or combinations of these

However, variable success complicates understanding efficacy
Project goal

• To determine whether existing data suggest that these methods may be effective enough to really replace or substantially reduce soil fumigant use in CA.

  – Question is not: “Does soil solarization [for example] work?”

  – But: “Does the **weight of evidence** suggest that soil solarization will work **consistently enough** in current **high-fumigant-use scenarios** in CA to allow growers to **reduce** their use of fumigants without dramatically **impacting yields**?”
The meta-analysis approach

• Considers all relevant studies on a clearly defined topic
• Statistically rigorous approach developed initially for analyzing data across controlled clinical trials
  – No true replication (unlike lab rats, human subjects not clones)
  – Large-scale trials very expensive
• Increasingly being applied to ecological data
  – For the same two reasons
• Replacing so-called “vote counting” approach in many cases
  – Where numbers of successful/unsuccessful studies dictate conclusions
  – Statistical tools of meta-analysis for determining “effect sizes”
  – Determining sources of variation in results between studies, based on differences in study design or environmental conditions
    • Focus on “Materials & Methods” as much as “Results”
    • Consider variables one-at-a-time
Sample of meta-analysis data

Fig 6. Relative yield data from the full meta-analyses and LSI intervals for alternatives compared to methyl bromide (67:33) from international research studies in strawberry fruit crops from 1997 to 2005 (Treatments with three or more observations).

Data for “compost” only 4 studies

Metam-Na only 78% as effective avg. of 80 studies
Sample of meta-analysis data

Forrest plot

<table>
<thead>
<tr>
<th>Study</th>
<th>Total</th>
<th>Mean</th>
<th>SD Total</th>
<th>Mean</th>
<th>Control SD</th>
<th>Standardised mean difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMD</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>562.00</td>
<td>37.5400</td>
<td>3</td>
<td>544.00</td>
<td>37.5400</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>835.00</td>
<td>61.7200</td>
<td>3</td>
<td>878.00</td>
<td>61.7200</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>678.00</td>
<td>21.4400</td>
<td>3</td>
<td>709.50</td>
<td>21.4400</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>600.00</td>
<td>37.0500</td>
<td>5</td>
<td>575.00</td>
<td>37.0500</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>36.50</td>
<td>3.6800</td>
<td>4</td>
<td>32.60</td>
<td>3.6800</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2.53</td>
<td>0.3162</td>
<td>4</td>
<td>2.53</td>
<td>0.3162</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>720.00</td>
<td>161.6700</td>
<td>7</td>
<td>857.90</td>
<td>161.6700</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>52.02</td>
<td>7.5000</td>
<td>4</td>
<td>50.36</td>
<td>7.5000</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>33.30</td>
<td>3.3200</td>
<td>4</td>
<td>34.40</td>
<td>3.3200</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>16803.00</td>
<td>3336.2800</td>
<td>4</td>
<td>28346.00</td>
<td>3336.2800</td>
</tr>
</tbody>
</table>

Fixed effect model: 41
Random effects model: 41

Heterogeneity: $I^2 = 21.6\%$, $tau^2 = 0.1590$, $p = 0.2446$
Steps in meta-analysis

1. Clearly define criteria for including a study
2. Systematically identify & obtain relevant studies
3. Design data entry sheets to capture relevant experimental parameters
4. Data entry
5. Data clean-up (uniform units, etc.)
6. Determine which parameters have sufficient data to allow statistically robust meta-analysis
7. Analysis
1. Criteria for including a study

1. Key CA crops/pests against which fumigants now used
   a) strawberry, carrot, tomato, potato, grape, almond, walnut
   b) e.g., root-knot nematode, but not reniform nematode, in potato

2. Alternative management practices
   a) Soil solarization/ biofumigation
   b) Anaerobic soil disinfestation (ASD)
   c) Non-fumigant chemicals
   d) Grafting/resistant varieties
   e) Soil-less culture
   f) Crop rotation (host/non-host)
   g) Steam or heat treatment
   h) Biological control agents

3. Compare directly to fumigant treatment AND untreated control
4. Quantify resulting key crop yield or key pest suppression
5. Published 2002 to date
6. Field or greenhouse study
2. Identifying relevant studies

A. Search query

– **Fumigant terms:** ((fumiga* not fumigatus) or nonfumiga* or "methyl bromide" or "bromo methane" or "methyl iodide" or iodomethane or chloropicrin or dichloropropene or "metam potassium" or "metham potassium" or "metham sodium" or "metham sodium" or telone or midas or vapam or dazomet)

– **Key crop/pathogen terms:** (tomato* or strawberr* or carrot* or potato* or ((grape* not grapefruit*) or tablegrape* or winegrape* or vineyard*) or walnut* or almond* or meloidogyne or "root knot" or phytophthora or verticillium or nedsedge or cyperus or rhizoctonia or pratylenchus or "root lesion" or pythium or xanthomonas or macrophomina or ramularia...)

– **Management practice terms:** ((soil and disinfest*) or biosolariz* or biofumiga* or mycofumiga* or solarization or "hot air" or "impenetrable film"* or rotat* or plasticulture or soilless or "soil less" or bagasse* or coconut* or coir or peat or mulch* or "organic amendment"* or brassica or brassicaceae or medicago or compost* or manure* or "anaerobic soil disinfestation" or (soil and steam) or (soil and heat) or ((susceptib* or resistan*) and root*) or biocontrol or "bio control" or "biological control" or Trichoderma or "dimethyl disulfide" or "dimethyl disulphide" or dmds or biofence or bioprem or "essential oil**" or glucosinolate* or methylsulfide or methylsulphide or nemaclean or paecilomyces or paecil or bioact or paladin or pochonia or multigard or furfural or acrolein or oxyfluorfen or propozone or "cover crop**" or graft* or avermectin* or abamectin* or azide or C2N2 or ethanedinitrile or formulat* or isothiocyanat* or jasmon* or mustard or pasteuria or "propylene oxide")
2. Identifying relevant studies

B. Sources consulted

• Primary databases: CAB Abstracts, Biosis, Web of Science
• Secondary databases: Google Scholar, Chem Abstracts, Agricola, etc.
• Gray literature sources not consistently covered
  – Methyl Bromide Alternatives Conference Proceedings – 2002-2013
  – Plant Disease Management Reports (by APS) – 2002-2013
  – WorldCat
  – About 20 others such as “Calif Strawberry Commission Annual Res Reports” and “Proc Western Soc Weed Sci “
• Bibliographies of articles obtained
2. Identifying relevant studies

C. Screening retrieved articles

About 40% rejected for lack of original data or proper controls, for example...

Abstract

Control of soilborne pathogens of tomato using a commercial formulation of *Streptomyces griseoviridis* and solarization

Andrea Minuto, Davide Spadaro*, Angelo Garibaldi, Maria Lodovica Gullino

Centre of Competence for the Innovation in the Agro-environmental Sector (Agroinnova) and Di Va. P. R. A.—Plant Pathology, University of Turin, via L. da Vinci 44, 1-10095 Grugliasco (TO), Italy

Sphagnum peat present work was first to test S. griseoviridis and *Verticillium* for the control of Foliar diseases of tomato. The antagonistic effect of *Fusarium* and *Rhizoctonia* antagonistent was not effective against *Fusarium* crown and root rot caused by *F. oxysporum* f.sp. *radicis-lycopersici*, when applied alone, but was less effective when applied with *S. griseoviridis*. Soil solarization provided good control of *V. dahlieae* and *F. oxysporum* f.sp. *lycopersici*, but was also slightly less effective when combined with *S. griseoviridis*. A significant increase in fruit mass and a higher yield m⁻² was recorded when solarization and the biofungicide were applied together in 2001. This indicated there may be a potential additive effect of the commercial biofungicide and solarization in increasing tomato yield; however, it was not consistent and generally not significantly different from the inoculated control. Metham sodium provided the most effective control of corky root and greatest yield increase of all the treatments evaluated.
But no fumigated control in 2001 solarization studies, so solarization data excluded from our study

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Experimental protocols for the four trials carried out against different soilborne pathogens on tomato cv. Cuore di bue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First trial</td>
</tr>
<tr>
<td>Artificial inoculation&lt;sup&gt;a&lt;/sup&gt;</td>
<td>FORL (30 g m&lt;sup&gt;−2&lt;/sup&gt;), FOL (30 g m&lt;sup&gt;−2&lt;/sup&gt;), <em>Verticillium dahliae</em> (15 g m&lt;sup&gt;−2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Treatments with <em>Streptomyces griseoviridis</em> by irrigation (I) or by spraying (S)</td>
<td>10&lt;sup&gt;7&lt;/sup&gt; cfu m&lt;sup&gt;−2&lt;/sup&gt; (S)</td>
</tr>
<tr>
<td>Solarization (26 days)</td>
<td>Alone and followed by Mycostop® application</td>
</tr>
<tr>
<td>Chemical control</td>
<td>—</td>
</tr>
<tr>
<td>Harvest</td>
<td>December 2001</td>
</tr>
</tbody>
</table>

Query & screening results (to date) by source

• Three primary databases (as of 4 Feb 2014)
  – Retrieved: CAB (926), Biosis (637), WoS (726)
  – Retained: CAB (352), Biosis (247), WoS (179)
  – Total retained from all 3 databases: 490

• Other sources
  – Retrieved: (didn’t count, since searched manually)
  – Retained: 264

• Total retained from searches: 490 + 264 = 754

• Rejected during thorough full-text screening
  – 145 (so far, ongoing process)
## Query & screening results (to date) by crop

<table>
<thead>
<tr>
<th>Total lbs fumigant</th>
<th>Strawberry</th>
<th>Carrot</th>
<th>Tomato</th>
<th>Potato</th>
<th>Grape</th>
<th>Almond</th>
<th>Walnut</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 35 mil</td>
<td>8,410,682</td>
<td>6,610,986</td>
<td>4,121,222</td>
<td>1,465,187</td>
<td>893,876</td>
<td>781,477</td>
<td>472,399</td>
</tr>
<tr>
<td>2009 30 mil</td>
<td>7,883,522</td>
<td>4,185,599</td>
<td>4,084,552</td>
<td>1,356,369</td>
<td>741,990</td>
<td>654,555</td>
<td>638,643</td>
</tr>
<tr>
<td>2010 34 mil</td>
<td>9,264,503</td>
<td>6,342,145</td>
<td>3,414,470</td>
<td>1,492,435</td>
<td>883,152</td>
<td>984,646</td>
<td>531,398</td>
</tr>
<tr>
<td>2011 38 mil</td>
<td>10,383,090</td>
<td>5,839,456</td>
<td>3,859,713</td>
<td>1,696,896</td>
<td>1,640,145</td>
<td>1,249,795</td>
<td>650,058</td>
</tr>
<tr>
<td>2012 41 mil</td>
<td>12,173,904</td>
<td>6,456,858</td>
<td>3,708,525</td>
<td>1,565,210</td>
<td>1,251,956</td>
<td>1,129,332</td>
<td>538,249</td>
</tr>
<tr>
<td>Avg 36 mil</td>
<td>9,623,140</td>
<td>5,887,009</td>
<td>3,837,696</td>
<td>1,515,219</td>
<td>1,082,224</td>
<td>959,961</td>
<td>566,149</td>
</tr>
<tr>
<td>Pct 100.00%</td>
<td>26.64%</td>
<td>16.30%</td>
<td>10.63%</td>
<td>4.20%</td>
<td>3.00%</td>
<td>2.66%</td>
<td>1.57%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAB articles</th>
<th>179</th>
<th>17</th>
<th>277</th>
<th>82</th>
<th>31</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ CDFA 2012</td>
<td>2.12 bil</td>
<td>0.50 bil</td>
<td>1.17 bil</td>
<td>0.19 bil</td>
<td>4.45 bil</td>
<td>4.35 bil</td>
<td>1.35 bil</td>
</tr>
</tbody>
</table>

Carrots account for 16.30% of pre-plant soil fumigant use in CA but only 2.8% of the research.

Sources: PUR Data; CDFA Annual Agricultural Statistics; CAB Abstracts database queries
Query & screening results (to date) by practice

<table>
<thead>
<tr>
<th># articles</th>
<th>Management practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>Biological control agents (microbials)</td>
</tr>
<tr>
<td>215</td>
<td>Chemicals other than MeBr or 4 alternative fumigants</td>
</tr>
<tr>
<td>6</td>
<td>Formulation of fumigants</td>
</tr>
<tr>
<td>40</td>
<td>Grafting or resistant varieties</td>
</tr>
<tr>
<td>46</td>
<td>Crop rotation or cover crops</td>
</tr>
<tr>
<td>9</td>
<td>Soilless culture</td>
</tr>
<tr>
<td>32</td>
<td>Steam, applied heat or hot water</td>
</tr>
<tr>
<td>42</td>
<td>Compost (organic matter without plastic sheet)</td>
</tr>
<tr>
<td>83</td>
<td>Bare soil solarization (plastic sheet without organic matter)</td>
</tr>
<tr>
<td>57</td>
<td>Biosolarization/ASD (with both organic matter &amp; plastic sheet)</td>
</tr>
</tbody>
</table>
Distribution of solarization and ASD studies

Vast majority on strawberries or tomatoes
Steps 3 & 4. Extracting relevant data

One replicate block from hypothetical field trial

<table>
<thead>
<tr>
<th>Solarized</th>
<th>Solarized</th>
<th>Not solarized</th>
</tr>
</thead>
<tbody>
<tr>
<td>no organic</td>
<td>Brassica*</td>
<td>Not FUM</td>
</tr>
</tbody>
</table>

Fumigated

<table>
<thead>
<tr>
<th>Solar</th>
<th>Solar Brassica</th>
<th>UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FUM</td>
</tr>
</tbody>
</table>

Not Fumigated

Expected results:

<table>
<thead>
<tr>
<th></th>
<th>Nematode population</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTC</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>FUM</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Solar</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Solar-Brassica</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

The gap between UTC and FUM is:

1. The measure of FUM benefit;
2. The scale by which to gauge the “efficacy” of solarization (with or without Brassica matter) relative to standard fumigation.

*NOTE: Brassica crop residues release toxic isothiocyanates upon decomposition.
Example using real data

<table>
<thead>
<tr>
<th></th>
<th>Strawberry yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/plant</td>
</tr>
<tr>
<td></td>
<td>% increase vs. UTC</td>
</tr>
<tr>
<td>Untreated control (UTC)</td>
<td>610.4c</td>
</tr>
<tr>
<td>MBr:Pic (67:33) 392 kg/ha</td>
<td>857.9ab</td>
</tr>
<tr>
<td>Solarization*</td>
<td>720.0bc</td>
</tr>
</tbody>
</table>

*3-weeks, no organic matter, incl. 53h above 40°C at 5-cm soil depth

Efficacy of solarization relative to a very strong fumigant control:
Yield increase: 18.0/40.5 = 44.4% as effective as fumigation

Solarization was only marginally successful here vs. fumigant, but consider:
1. Since few growers can use 2/3 MeBr fumigant, is this proper comparison?
2. How effective would it have been if...e.g., *Brassica* waste was included?

Source: Samtani, et al. “Effect of steam and solarization treatments on pest control, strawberry yield, and economic returns relative to methyl bromide fumigation”. *HortScience* **47**: 64-70 (Table 5)
Meta-analysis can determine overall impact of individual variables by quantifying within-study impacts

Variables commonly tested individually:

- Solarization alone often compared with combinations of...
  - Organic matter (non-Brassica or Brassica)
  - Biological control agents
  - Non-fumigant pesticides
  - Reduced fumigant application rates
- Soil depth of pathogen suppression
- Film characteristics

For each of above, often report data...

- different locations in same season
- different seasons at same location (year-to-year variation)

For example, if 15 of the 83 studies compared yields in solarized plots with and w/out Brassica crop residues directly, we can calculate the mean effect size (and 95% confidence interval) of including Brassica crop residues on yield for those 15 studies.
Variables recorded for each treatment value

General experimental design features

- Citation
- Geographic location (lat/long)
- Soil characteristics
- Soil temperature data
- Sample size
- Number of replicates
- Fumigant treatment (composition & application rate)
- Plastic film characteristics
- Crop/variety
Variables recorded for each treatment value

Those for single datum

• Treatment variables
  – Organic matter: fresh chicken manure, 15 t/ha
  – Season: 1998

• Endpoint type (“yield”)

• Measured endpoint (“total marketable yield”)

• Treatment value & units (562 g per plant)

• Treatment variance, var type & stat group (NA/NA/“a”)

• UTC value, variance & stat group (319/NA/“c”)

• FUM value, variance & stat group (544/NA/“a”)

• Statistical test & data transformation (Duncan’s multiple range)

• Independent group (arbitrary—re-sampling or sub-sampling)
5. Data clean-up (Example 1 - Data uniformity)

Success of solarization requires high soil temperatures, but studies differ in how soil temperature data are reported.

Some give one value for each day of solarization at various soil depths:

- Maximum 15 cm
- Maximum 5, 10 & 15 cm
- 2:00 PM 5 & 10 cm Interpolate
- 2:00 PM 5, 10 & 20 cm (15 cm)
- 2:30-3:00 PM 5, 15 & 30 cm (10 cm)

Some give cumulative number of hours above biologically-relevant thresholds at various soil depths:

- 30, 35, 40 & 45°C 2 & 20 cm (10 & 15 cm)
- 37, 40 & 45°C 15 cm
- 38, 43 & 48°C (40 & 45°C) 15 & 30 cm
- 40 & 42.5°C 15 cm
- 40, 45 & 50°C 0, 10 & 20 cm (15 cm)
- 40, 46, 51 & 56°C (45°C) 10, 20 & 30 cm (15 cm)
Solve equations to obtain values for 40 & 45°C to be consistent with other studies.

Note the dramatically different temperatures generated by plastic films tested here.
Data clean-up (Example 2-Graphical to tabular)

Brilliant program: WebPlotDigitizer ([http://arohatgi.info/WebPlotDigitizer/](http://arohatgi.info/WebPlotDigitizer/))

1. Copy/paste figure onto a 968 x 1096 grid
2. Define the axes
3. Choose points by clicking mouse
About 20 minutes later... 265 points selected.

Known X-axis values of 265 points yields 99.7% accuracy of manually obtained values, based on Relative Absolute Error of known & obtained values.

Relative Absolute Error: 
\[ E_i = \frac{\sum_{j=1}^{n} |P_i - T_j|}{\sum_{j=1}^{n} |T_j - \bar{T}|} \]

X-coord,Y-coord
0.25573,38.67647
0.73879,39.02941
1.24185,41.32353
1.73333,42.38235
2.26639,45.00000
2.75628,45.35294
3.23934,44.94118
...
Accuracy possible due to (i) ~1000 X ~1000 grid & (ii) ~80-100-fold magnified view of cursor position.

Left of center by 2 grid lines 1 grid line

Centered
Overall project has some statistical challenges

- Many studies do not report quantitative variance
  - Must integrate disparate statistical methods to measure variation

- "Sample size" is best represented by number of replications
  - Abiguous: "average of replicate means" or "means of replicate averages"

- Lack of standardized protocols requires much interpolation & transformation of data
In conclusion...

• Several hundred relevant studies identified
  • Data is being entered and processed

• Project is a work-in-progress
  • We will hire a few graduate students this summer
  • Statistical tools are being developed to integrate data
    • within and across studies

• Results not available yet beyond preliminary Forrest plot
  • More research should focus on carrots
    (which account for 1/6 of all fumigant use in CA)