The Importance of Soil Fumigation:

California Strawberries
The Importance of Soil Fumigants in California Strawberry Production

Introduction

With a value of over $2.4 billion in 2012, strawberries are the third most valuable fruit produced in the U.S., following grapes and apples [1]. Strawberries are second only to apples in value of fresh market sales, which account for the vast majority of production and value, with 2.4 billion lbs of production valued at $2.2 billion in 2012 [2][3], and they are the fifth highest consumed fresh fruit in the U.S., behind bananas, apples, oranges and grapes [6]. Consumption in the U.S. has increased from 1.97 lbs/year in 1980 to 7.37 lbs/year in 2011 [6].

The U.S. is the world’s largest strawberry producer, with 30% of global production in 2010, followed by Turkey (7%), Spain (6%) and South Korea, Mexico and Egypt with 5% each [4]. Canada is the largest US export market for strawberries, with 88% of total fresh strawberry exports and 50% of total frozen strawberry exports in 2011, followed by Japan with 3% of fresh strawberry exports and 33% of frozen strawberry exports. And Mexico provides the largest share of imports with 90% of combined fresh and frozen strawberry imports [4]. About a third of total imported volumes arrive in the U.S. during the months of March and April [4].

Although total U.S. strawberry acreage is only 11% higher in 2012 compared to 1970, total production is nearly six times greater, due to yields that have increased from an average of 9,800 lbs/acre in 1970 to 53,700 lbs in 2012 [2][4]. While yields have increased across strawberry production areas of the U.S., the most dramatic increases have occurred in California, where yields increased from 34,000 lbs/acre in 1970 to 72,000 lbs/acre in 2012 [2][4]. (See Figure 1.)

The high productivity of strawberries in California can be attributed to the yield potential of the cultivars grown, the mild coastal climates that are ideal for strawberries, an extended harvest, the use of annual production systems that use pathogen- and pest-free planting stock each year, and the intensive management of the crop with a third of the state’s acreage being replanted after a one year rotation to an alternate crop [11] [12]. The dominance of California has coincided with a decline in other production areas, such as Oregon, which was the largest strawberry producing state in 1970. Increased supplies of frozen berries from Mexico, as well as expanding California production, brought low processing prices, which led to a contraction in planted acreage in Oregon [5].

California is the leading strawberry growing state, producing 92% of the US total in 2012 and accounting for 88% of total crop value, followed by Florida (6% of production and 8% of value), North Carolina (0.7% of production and 1.2% of value) and Oregon (0.7% of production and 0.6% of value) [2]. Grown on less than 0.5% of total California cropland, strawberries are the sixth most valuable agricultural product in California, after milk and cream, shelled almonds, grapes, cattle and calves, and nursery crops [7][8][56].
California Strawberry Production Areas

The rich sandy soil and temperate climate along the California coast are well suited for strawberry production, with production areas stretching for 500 miles from San Diego to Monterey (Table 1). Production begins in the south and proceeds north. Planting occurs mostly in the fall, for winter, spring and summer production, with a small portion planted in the summer. In 2012, about 10% of California strawberry acreage was planted in the summer for fall production, primarily in Oxnard (Ventura County) and Santa Maria (Santa Barbara County) [10]. Fall plantings in San Diego, Orange, Los Angeles and Ventura counties begin production in early January (sometimes late December) and continue through June with fresh-market shipments usually peaking in April. In the Santa Maria area, north of Oxnard, harvest usually starts in March and continues into July. Deliveries to processors in Santa Maria continue through August. California’s northern strawberry growing region is south of San Francisco and includes Santa Cruz and Monterey Counties and some acreage in Santa Clara and San Benito counties. The cities of Watsonville and Salinas account for almost half of the state’s strawberry acreage. Shipments from northern areas begin in April, peak in May or June, and continue through November [12]. Fresh market production accounted for approximately 80% of total California strawberry production and over 90% of value between 2010 and 2012 [2].

Cultural Practices

All of California’s strawberry acreage is irrigated and most of the crop is grown on an annual basis. Until recently, in essentially all but organic acreage, fields were fumigated with a combination of methyl bromide and chloropicrin under a sealed plastic tarp several weeks before planting [11]. Fumigation with methyl bromide and chloropicrin has typically been performed on flat ground over the entire surface of the field. At the end of the fumigation period, the plastic is removed and planting beds are formed and covered with fresh plastic [46]. Due to the phase-out of methyl bromide, alternative fumigants are increasingly used. (See discussion below.) Currently, over 55% of California strawberry acres are drip fumigated, as chloropicrin and 1,3-dichloropropene may be applied to raised beds through drip irrigation systems [30]. Planting beds are covered with polyethylene mulch, which helps regulate soil temperature, conserves soil moisture, reduces salinity build up on the soil surface, and reduces decay problems by limiting fruit contact with soil and irrigation water. Preplant weed control is critical unless opaque mulch is used, because clear and translucent mulches do not control weed growth. The type of mulch used and timing of application depend on cultivar, planting and harvest seasons, and other management practices [30]. Strawberry plants are transplanted about two to six weeks after fumigation to ensure that there are no phytotoxic levels of fumigant remaining. Harvest begins about two to four months later [46]. Hand-harvesting continues for several months on a 3 to 5 day cycle. This continual harvesting ends when productivity declines significantly [11]. At the end of the first harvest, the strawberry plants are removed and the field is readied for the next crop. Rotational crops that are planted after strawberries, and that benefit from the previous fumigation, include broccoli, celery, lettuce, radish, leeks, and artichokes [46].
Major Target Pests

Soil fumigants are routinely used to control a range of soilborne diseases and weeds.

Verticillium wilt, caused by the pathogenic soilborne fungus, Verticillium dahliae, has historically been a major constraint in strawberry production in California [47]. Verticillium dahliae is a widespread soilborne fungus that survives as dark multicellular structures known as microsclerotia. When a plant root grows in close proximity to microsclerotia, Verticillium can germinate and infect the root. The infections can extend into the plant’s water conducting tissue, which can distribute the fungus throughout the plant, causing varying degrees of wilt, stunting and/or dieback. Microsclerotia can survive for several years in soil. Once an infestation has become established in a field, it is likely to persist unless extraordinary measures are taken to eradicate the pathogen. Even in fields where pre-plant fumigation has been applied for many years, the fungus can still be detected [47]. Crops such as potato and lettuce, which are rotated with strawberry are susceptible to the same strain of V. dahlia that causes disease in strawberries [48].

Beginning in 2005, charcoal rot caused by Macrophomina phaseolina has emerged as the most threatening new soilborne disease for California strawberry production. The disease has been confirmed in all of the major strawberry production areas of the state, and the number of infested farms is increasing. In most cases, the disease has been found in plantings that did not receive the standard pre-plant flat fumigation with methyl bromide and chloropicrin. Symptoms of plants infected with M. phaseolina consisted of wilting of foliage, plant stunting, and drying and death of older leaves, with the central youngest leaves often remaining green and alive for a period of time after disease onset. Plants eventually collapsed and died [49].

Starting in 2007, cases of plant collapse have been associated with another soilborne disease, Fusarium oxysporum, and has become a serious problem in southern California production areas, which has also been linked with changes in fumigation practices. Fusarium oxysporum causes a wilt disease by invading the plant’s water conducting tissue[47]. The symptoms of Fusarium wilt and charcoal rot are exactly the same [49]. The emergence of new diseases in strawberry production areas since the phaseout of methyl bromide has also been observed in Israel [55].

In addition to lethal pathogens such as Verticillium, Macrophomina and Fusarium, fumigation also controls a complex of sublethal competitive soil organisms, such as Pythium spp., resulting in an increased growth response [14].

Soil fumigation with methyl bromide has also provided effective weed control in strawberry production. Strawberries are very sensitive to weed competition, especially right after planting when the plants are small and frequent irrigation provides ideal conditions for weed germination [30]. Weeds can also harbor harmful diseases and insects. With recent changes in fumigation practices, weed control
challenges have emerged, such as yellow nutsedge, as alternative fumigants are not as effective against this weed [50]. Hand weeding is recommended for nutsedge plants appearing in strawberry fields [30].

Soil fumigation with methyl bromide and chloropicrin has controlled certain arthropods such as root weevils, cutworms, strawberry rootworms, white grubs, garden symphylan and brown mealy bug, as well as nematode species. These pests directly impact strawberry yields and or quality when present at sufficient levels [51].

**Fumigant Use and Restrictions**

The potential benefits of soil fumigation for California strawberry production were first tested in the 1950’s. A 1953 experiment using 480 lbs/acre of chloropicrin resulted in first and second year yields of 9.8 and 16.7 tons per acre, compared to normal yields of 4 and 7.6 tons per acre on land fumigated with ethylene dibromide [13]. The idea of mixing chloropicrin and methyl bromide was first tested in 1957 and 1958, finding that the fungicidal properties of chloropicrin was augmented by methyl bromide, which also controlled weeds.

Soil fumigation with combinations of methyl bromide and chloropicrin became an integral part of strawberry cultivation in California around 1960, due to control of Verticillium wilt, other soilborne diseases and weeds and resulting dependably higher yields, as well as enabling other changes in crop management. Effective weed control with fumigation led to the practice of covering plant beds with clear polyethylene film to shield fruit from contact with soil, and by eliminating the need for cultivation, made possible the use of drip irrigation. Fumigation also allowed the realization of the yield potential of cultivars developed by the University of California and by Driscoll Strawberry Associates, which had been severely hampered by soilborne diseases. Prior to the use of fumigants, strawberry production in California was considered speculative, characterized by uncertain yields and a constant search for new land that had not been recently cultivated to crops such as tomatoes, potatoes and cotton [13].

Until recently, soil fumigation with methyl bromide and chloropicrin was performed on nearly all California strawberry acreage. A series of regulatory actions at the federal and state levels has curtailed the use of these fumigants, as well as 1,3-D, and additional regulatory measures are under consideration that are expected to further limit the use of fumigants.

In 1992, parties to the Montreal Protocol, an international treaty limiting the production and consumption of ozone-depleting substances, added methyl bromide to the list of class-I ozone depleters that are required to be phased out. As a party to the Protocol, the U.S. amended the Clean Air Act in 1998 to align with the phase-out schedule for methyl bromide as agreed by the parties to the Montreal Protocol, which required a 25% reduction in production and consumption from 1991 levels in 1999, 50% in 2001, 70% in 2003 and a total phase-out beginning in 2005 with allowable exemptions for critical uses and quarantine and pre-shipment [18] [19]. The U.S. has made annual requests for critical use exemptions for specific uses for each year since 2005. On January 24, 2013, the U.S. transmitted its eleventh nomination for a critical use exemption for methyl bromide use in 2015, which included fresh
dates, dry cured ham and strawberry fruit [20]. The nomination for strawberry fruit requested 373,660 kg of methyl bromide [21].

In 2000, the California Department of Pesticide Regulation announced field soil fumigation use requirements for methyl bromide to control volatile organic compound (VOC) emissions and toxic exposure. The DPR requirements included: the establishment of buffer zones around treated areas of at least 50 feet where no one is allowed to enter except for transit or to perform fumigation activities for 36 hours following fumigation (inner buffer), at least 60 feet where no occupied residences or occupied onsite employee housing, schools, convalescent homes or hospitals (outer buffer); a requirement that when a school property is located within 300 feet of the perimeter of the outer buffer, fumigation must be completed at least 36 hours prior to times when students would attend classes; delineation of fumigation methods with associated maximum application rates; a maximum block size of 40 acres; notification requirements and limited work hours for pesticide workers [22]. In 2013, CDPR revised methyl bromide zone determinations to align with EPA. The revisions did not change buffer zone distances, but did increase buffer zone durations for most fumigations [26].

The use of 1,3-dichloropropene (1,3-D) was suspended in California in April 1990 after monitoring detected levels above air quality standards in Merced County [23]. Its use was reinstated in 1995 with restrictions including reduced application rates, buffer zones, and lengthened reentry intervals. Restrictions were subsequently modified to limit total 1,3-D use within 36-square mile areas, known as townships, to 90,250 lbs per year, with lower limits if any applications were made at a depth of less than 18 inches or during December or January. Through 2001, 1,3-D use was limited to 90,250 lbs per year in all but five townships where DPR authorized an increased allocation due to the methyl bromide phaseout which made methyl bromide unavailable to growers in some areas. The increased allocations were made only in areas where 1,3-D use was below the 90,250 lbs per year cap. In 2002, DPR formalized an alternative management plan that would allow 1,3-D use above the 90,250 lbs township limit, up to 180,500 lbs per year to the extent that use since 1995 in that township was under the 90,250 lbs annual limit [24].

Regulatory restrictions on the use of methyl-isothiocyanate generating pesticides (metam sodium, metam potassium and dazomet) were announced in November 2010, with the publication of recommended permit conditions for the County Agricultural Commissioners who grant permits for application of restricted use pesticides, which included buffer zones, maximum application rates and block sizes and notification requirements [25].

In 2009, EPA issued Amended Reregistration Eligibility Decisions for the soil fumigant pesticides, chloropicrin, dazomet, metam sodium/potassium and methyl bromide. The RED’s included safety measures intended to increase protection for agricultural workers and bystanders, and have been implemented in two phases. The phase one changes went into effect on December 31, 2010, including respiratory protection for agricultural workers handling fumigants, tarp handling requirements, an entry-restricted period, training, and restrictions on application methods and rates. Phase 2 changes went into effect on December 1, 2012, including buffer zones around treated fields, credits for reduced
buffer distances for the use of high-barrier tarps, signage around fumigation sites, and site-specific management plans [27).

On May 15, 2013, the DPR proposed new risk mitigation measures for chloropicrin. Compared to the EPA mitigation measures, DPR is generally proposing the following: longer buffer zones, extended time period between applications with overlapping buffer zones, and eliminating some buffer zone credits based on a more protective approach for estimating flux (off-site air concentrations) for different application methods [17]. The US EPA phase two labels establish buffers depending on application method, block size and rate, then gives buffer zone credits of up to 80% that reduce the size of the buffer zone for the following factors: tarp type, organic matter, clay content, soil temperature, Symmetry System, potassium thiosulfate (KTS), and water seal applied over the tarp. The DPR mitigation measures may differ from the US EPA approach, particularly with respect to factors allowed in the calculation of credits [27].

Additional restrictions on the use of fumigants have been put into place to reduce emissions of volatile organic compounds (VOC’s) from field fumigants in five ozone nonattainment areas (NAA’s), under California’s State Implementation Plan for the Clean Air Act. The five NAA’s affected by the VOC regulations are Sacramento Metro, South Coast, San Joaquin Valley, Southeast Desert, and Ventura. In the Sacramento and South Coast NAA’s, where pesticide VOC’s have already been reduced below emission targets, only certain standardized fumigant application methods can be used between May 1 and October 31. In the San Joaquin Valley, Southeast Desert and Ventura NAA’s, only low-emission methods can be used between May 1 and October 31. These methods are expected to be sufficient to achieve required VOC reductions in the San Joaquin Valley and Southeast Desert NAA’s, but fumigant limits have been established in Ventura County [15]. In order to ensure that fumigant use does not exceed the limits established by DPR, may impose an allowance system [29].

In April 2013, DPR granted interim approval for the use of TIF tarp methods in the NAA’s, with emissions ratings for certain TIF tarp application methods which reduce emissions potentially allowing growers to use desired rates that might otherwise not be allowed if emission allowances go into effect [16].

These changes in regulations have resulted in shifted patterns of fumigant use. Figure 2 shows trends in the use of 1,3-D, chloropicrin, metam sodium and methyl bromide from 1998-2011. In terms of percentage acres treated, methyl bromide use has declined from use on over 80% of strawberry acreage before 2001 to 31% in 2011. 1,3-D use has climbed from use on less than 1% of strawberry acres in 1998 to 47% in 2011. Metam sodium use has climbed from 2.6% of acres treated in 1998 to 6.9% in 2011. Chloropicrin use has been fairly stable.

**Alternatives to Fumigants**

The long-term viability of soil fumigants has been questioned due to rising costs, limited efficacy and use restrictions [31]. The California Strawberry Commission began funding the Farming Without Fumigants Initiative in 2008, with the goal of developing strawberry fruit production methods that can avoid the
The complexities of highly regulated fumigants [32]. In 2012, the California Department of Pesticide Regulation convened a working group of industry and scientific leaders to develop an action plan of research priorities for developing cost-effective management tools and practices for soilborne pests of strawberries in the absence of conventional fumigants [31]. The action plan acknowledged that many studies had been done over the past 20 years on non-chemical alternatives to methyl bromide, including anaerobic soil disinfestation, biopesticides, biofumigants, soilless substrate, steam, and solarization. At the same time, the CSC and CDPR announced a partnership to look for alternatives to fumigant pesticides through a three-year, $500,000 project focused on growing strawberries in peat or substances other than soil [33].

Here we discuss the efficacy, yields and costs of several potential alternatives to currently used soil fumigants in California strawberry production.

**Steam**

Steam has been used since the 1880’s to kill soilborne pests including fungi, weeds, nematodes, and insects [39]. Steam soil treatments that raise the temperature to 70°C for 20 minutes kills most soil pathogens and weed propagules. Several years of trials in strawberry production areas of California have found that steam kills weed seeds and pathogens as effectively as soil fumigants, and strawberry yields are comparable to those achieved with fumigation [40]. Due to the very slow and energy intensive nature of traditional steam application methods, researchers have developed a prototype single bed automatic steam applicator [40]. Operations costs for this prototype have been calculated at $5500 per acre, including fuel, labor and machine costs [40].

Further improvements to steam soil treatment application strategies are being pursued to increase fuel and labor efficiencies, including physical soil mixing to reduce treatment time, the use of exothermic compounds to improve pest control and the potential complementarities between steam and the use of biofumigants such as mustard seed meal [31][39][40]. Additional research needs have been identified including the design of steam generators to adopt technology that allows the use of hard or soft water, the design and building of a steam applicator that treats several acres per day, and the determination of the optimal soil depth of treatment to protect strawberry roots and minimum treatment temperature needed to control soil pests [31]. A prototype propane-powered steam rig with downhole steam generation using hard or soft water that can treat 2 beds at a time at a rate of between 4 and 8 hours per acre is currently under development and is expected to be ready for trials in 2014. Preliminary cost estimates for this type of steam treatment system indicate a per acre cost of $3700. Further refinements of the steam treatment system may reduce costs even further [41].

*Anaerobic Soil Disinfestation*
Anaerobic soil disinfestation (ASD) integrates principles behind solarization and flooding to control soilborne pests in situations where neither is effective or feasible. ASD is characterized by the incorporation of easily-decomposable soil amendments (e.g. wheat or rice bran, fresh crop residues, molasses), irrigation to increase soil moisture content and tarping with polyethylene mulch for a period as short as two weeks to as long as fifteen weeks. The carbon from soil amendments combined with high soil moisture stimulates rapid growth of aerobic microorganisms, which depletes soil oxygen and induces a shift in soil microbial communities. As the anaerobic conditions form, soilborne plant pathogens and plan-parasitic nematodes are controlled, although the mechanism is not entirely clear [35].

In five years of studies aimed at optimizing ASD for use in California strawberry production systems, ASD has been shown to be consistently effective at suppressing Verticillium dahliae¹ and trials in Watsonville and Castroville have achieved marketable yields equal or higher than Pic-Clor 60 (56.7% chloropicrin + 37.1% 1,3-dichloropropene) plots. Additional trials compared ASD, steam, mustard meal and organic acids, alone and in combination on fruit yield, survival of pathogens, weed control, soil chemical and biological characteristics and economics [34]. Preliminary economic analysis has been conducted comparing ASD treatments to Pic-Clor 60, finding that net revenue above harvest and treatment costs were highest for ASD with 9 tons/acre of rice bran [36]. Table 2 shows a comparison of treatment costs, yields and net revenues for ASD treatments as calculated based on results from an experiment in Castroville 2010-2011. Overall results indicated that ASD and ASD+mustard meal were the most consistently effective and economically feasible non-fumigant alternatives to date [34][36].

However, ASD technology as tested did not provide weed suppression comparable to fumigation and herbicides may need to be added in severely infested sites. Researchers continue to explore methods to reduce nitrogen input from the carbon source to reduce the potential for excess nitrate to be lost into the environment or cause salinity damage to strawberry plants. Researchers have also identified the need to evaluate feasibility and cost effectiveness of ASD at a commercial scale and to further understand the modes of action that contribute to observed disease control [34]. In addition, there is a need to identify and test alternative carbon sources to rice bran, which would not be available in the quantity needed for California strawberry acreage. Further work is also needed to determine whether ASD can work in very sandy soils or on sloped fields [31]. Additional research will be needed to demonstrate efficacy against newly emerging diseases, charcoal rot and fusarium wilt, as well as to address the potential for pest build up in fields treated with ASD for more than one year. Trials that are currently underway for the 2012-13 season include demonstration and commercial scale trials and include molasses as an alternative carbon source [54].

*Raised-bed Trough System*

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¹ ASD was shown to be consistently effective when 9 tons/acre of rice bran was pre-plant incorporated and 3 to 4 acre-inches of irrigation was applied in sandy-loam to clay-loam soils.
A raised-bed trough (RaBeT) system has been developed using beds constructed from field soil, creating troughs on the beds and filling them with sterile soilless media. Various materials have been used as substrates in commercial strawberry production in Europe, including peat moss, coconut coir, perlite, rockwool, pinebark or combinations of these materials, in different types of containers. The growth media is separated from the ground by a barrier fabric to prevent or minimize the contact between strawberry roots and diseases that may be present in the soil beneath the fabric and to control weeds. Nutrients and water are supplied through fertigation systems [42].

Field trials at three locations in 2009-2010 evaluated 6 different substrate-based treatments compared to the grower standard soil fumigation. Yields comparable to the fumigated standard were found in four of the six substrate-based treatments at one site, while yields were significantly higher in the fumigated standard than all substrate-based treatments at a second site, which was attributed to replanting that was performed in the trough system treatments. At a third site, yields were all similar except for all treatments except one of the substrate-based treatments [42].

Further trials were performed in 2010-11 with the primary objective of improving production in the best substrates and to evaluate the performance of an amended soil treatment combining substrate and clean soil to reduce costs of substrates. The high cost and limited availability of substrates have been identified as the primary obstacles to potential implementation of the RaBeT production system [31][43][44]. Results of the 2010-11 trials suggested that the RaBeT system can match yields of the grower standard and that the substrate and soil combination may be a viable approach for reducing costs [43]. Future research will address additional cost-reducing measures, including increased percentage of soil, reuse of substrate and reducing trough size. In addition, one acre demonstration trials will be conducted to evaluate the impacts of scaling up the system [43]. Additional needs that have been identified include the development of mechanical installation methods and complex automated systems for water and nutrient management [31].

**Biofumigants**

Biofumigation using Brassica residues that break down into isothiocyanates for disease and pest control has been evaluated for use in strawberry production systems. Researchers are studying the natural disease suppressive characteristics of soils and how to manage the resident biological forces to limit populations or activity of soilborne pathogens through a strategy of cropping practices or amendments. [45].

Recent research using mustard seed meal has focused on evaluating the capacity of *Bassicaceae* seed meals to suppress M. Phaseolina and to assess the capacity of wheat cropping with or without *B. juncea* seed meal amendment to suppress re-infestation of fumigated soils by *M. phaseolina* [45]. The seed meal formulation of *Brassica juncea/Sinapis alba* was found to suppress *M. phaseolina* but did not result in significantly higher strawberry plant growth or yield, which was associated with symptoms of phytotoxicity. Wheat cultivation of naturally infested strawberry field soil and artificially infested fumigated soil demonstrated suppression of *M. phaseolina*. However, the mechanism of suppression
was unknown and further investigation of the potential for wheat cultivation as a treatment for suppression of charcoal rot in strawberry production was deemed necessary [45].

Additional research needs related to biofumigants have been identified, including understanding the mechanisms of suppression of different pathogens by various species and mixes of mustard seed meal, and optimization of mixes of mustard seed meals to manage the range of pathogens of importance in strawberry [31]. Research on the combination of mustard seed meal soil treatments with other non-fumigant treatments, such as ASD and steam, are being studied, as discussed in the relevant sections above.

*Organic Production*

In order to be eligible for USDA organic certification, growers must farm on land to which no synthetic fertilizers or pesticides have been applied for a minimum of three years. Organic growers employ a range of practices such as crop rotation, cover crops and organic soil amendments to build soil fertility and manage pests.

Organic strawberry production in California has increased from 297 acres in 2000 (1% of California strawberry acreage) to 2,532 acres in 2013 (6.3% of acreage) [10]. Approximately one in five California strawberry farmers grow both conventional and organic strawberries [51]. With yields about 50% lower than conventional yields, organic strawberry production relies on a significant price premium and low costs of production [52][53]. In a standard organic rotation, strawberries are grown once every four or more years on a given field, which makes the system highly dependent on access to substantial quantities of certified organic land. In addition, organic production requires more than 75% more water than conventional strawberry production for the same amount of product [53][57].

*Estimated Benefits of Soil Fumigants*

California strawberry growers currently have very limited options if soil fumigants were no longer available, as the most promising non-fumigant alternatives are still being developed (steam), are too costly (raised-bed trough system) or face other constraints such as limited availability of materials (ASD and raised-bed trough system). Given that research and development continues for several promising alternatives, we consider three different timeframes, near, medium and long-term.

In the near term, California strawberry growers have few options for economic pest control if soil fumigants were no longer available. A 1997 USDA report estimated that strawberry yields without fumigants would decline by 70%. Organic strawberry production would be limited to acreage that is already certified organic until more acreage could be certified, a process that takes at least three years. Organic production would be further limited to areas with low disease pressure.
In the medium term (3 to 5 years), steam treatment using a downhole steam generator with soil mixing may be fully developed. It is estimated that a prototype will be tested in 2014, and if this system proves to be feasible and economic within the range of current estimates ($3700/acre), this technology could be scaled up within 2 to 3 years. Researchers estimate the treatment time for the downhole steam generator rig to be roughly 4-8 hours per acre. While this system may be the most promising in terms of pest control, yields, and treatment costs, it would take a significant capital outlay to make the steam rigs widely available. A 100 acre farm would take at least 33 days to treat with a single machine assuming a conservative 3 acres treated per day. A rig may cost in the range of $100,000. If 400 farms each bought one rig, the total cost of new machinery would be $40,000,000.

In the longer term (5 to 10 years), researchers may be able to refine anaerobic soil disinfestation approaches to a point where growers would be confident in their ability to achieve consistent pest control. This will require additional testing in plots with significant pest pressure in multi-year trials. In addition, alternative carbon sources would need to be identified, and other technical concerns (e.g. potential for nitrate leaching) would need to be resolved. The raised-bed trough system may also be refined adequately that it would also be an option in the longer term, as optimal soil-substrate mixes are determined, recycling schemes are developed and automated systems for nutrient and water management are implemented.
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57. Bolda, Mark, Laura Tourte, Karen Klonsky, Richard L. De Moura, 2010, Sample Costs to Produce Strawberries, Fresh Market, Central Coast, Santa Cruz and Monterey Counties, University of California Cooperative Extension, ST-CC-10,
Figure 1. California Strawberry Yields 1920-2012 (1,000 lbs/acre)

Sources: [4][7]
Table 1. California Strawberry Acreage by County and Region, 2012

<table>
<thead>
<tr>
<th>District</th>
<th>Fall Planted Acreage</th>
<th>Summer Planted Acreage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange County/San Diego</td>
<td>1,446</td>
<td>0</td>
<td>1,446</td>
</tr>
<tr>
<td>Oxnard</td>
<td>8,852</td>
<td>2,568</td>
<td>11,420</td>
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<tr>
<td>Santa Maria</td>
<td>8,385</td>
<td>1,140</td>
<td>9,525</td>
</tr>
<tr>
<td>Central Coast Region:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Watsonville/Salinas</td>
<td>14,187</td>
<td>12</td>
<td>14,199</td>
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<tr>
<td>San Joaquin Valley Region:</td>
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</tr>
<tr>
<td>San Joaquin</td>
<td>153</td>
<td>0</td>
<td>153</td>
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<tr>
<td>State Totals</td>
<td>33,023</td>
<td>3,719</td>
<td>36,742</td>
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</table>

Source: [10]
Figure 2. Fumigant Use in California Strawberry Production 1998-2010

Source: [38]
Table 2. Treatment costs, yields, and net revenues above treatment costs from Castroville 2010-2011 strawberry trials

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Cost (per acre)</th>
<th>Yield (lbs/acre)</th>
<th>Gross Revenue (per acre)</th>
<th>Net Revenue above harvest and treatment costs</th>
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</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>37,680</td>
<td>$35,042</td>
<td>$18,840</td>
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<tr>
<td>ASD1 :</td>
<td></td>
<td></td>
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<tr>
<td>rice bran 9 tons/acre</td>
<td>$1,675</td>
<td>40,631</td>
<td>$37,786</td>
<td>$18,642</td>
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<tr>
<td>3 weeks duration</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>3 acre inches water</td>
<td></td>
<td></td>
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<tr>
<td>ASD2 :</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rice bran 8 tons/acre</td>
<td>$3,098</td>
<td>40,608</td>
<td>$37,765</td>
<td>$17,206</td>
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<tr>
<td>mustard cake 1 ton/acre</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 weeks duration</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3 acre inches water</td>
<td></td>
<td></td>
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<td>ASD3 :</td>
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<td>rice bran 9 tons/acre</td>
<td>$1,741</td>
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<td>$18,354</td>
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<td>6 weeks duration</td>
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<td>6 acre inches water</td>
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<tr>
<td>ASD4 :</td>
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<tr>
<td>rice bran 8 tons/acre</td>
<td>$3,166</td>
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<td>$39,956</td>
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<td>mustard cake 1 ton/acre</td>
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<tr>
<td>6 weeks duration</td>
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<tr>
<td>6 acre inches water</td>
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<tr>
<td>Pic-Clor 60 300 lbs/acre</td>
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<td>37,013</td>
<td>$34,421</td>
<td>$17,706</td>
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Source: [36]