Banded Steaming for Weed and Disease Control in California Vegetables

By

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Abstract

Despite the overwhelming need for weed control in organic crops, there are currently no preemergence herbicides that are organic-compliant. As an alternative, steam injected into the soil, in which soil temperatures reach >70°C for 15-20 minutes will kill weed seed in the soil. The effect of this reduction in the seedbank viability results in control of weeds in the treated zone that can persist for several weeks or months, leaving the steamed soil area pasteurized. The effect of steam pasteurization on weeds seeds is similar to a preemergence herbicide. In my study, steam was applied alone and combined with hydrogen peroxide to create an exothermic reaction in the soil to kill weed seed and inoculum of *Sclerotinia minor* and *Pythium* spp. Replicated field trials in carrot, lettuce, and spinach were conducted using two types of banded steam applicators in 2020 and 2021. Data collected were soil temperatures after steam application, weed control, hand weeding times, diseased plant counts, and lettuce yields. Post-steam soil temperature intervals >70 °C in the top 4 inches of soil ranged from 67 to 176 minutes. Soil temperatures >70 °C in the steam + peroxide treatment were 76 and 80 minutes for trials 1 and 2, respectively. Steam and steam + peroxide reduced weed densities by 68-100% and reduced hand weeding times by 23-91%. The reduction of *S. minor* after steaming in all trials ranged from 77-94%. The reduction of *Pythium* spp. colonies after treatment in all trials ranged from 89-98% compared with the nontreated control. The lettuce head diameters in all trials ranged from 12-24% larger compared with the nontreated control. Carrots grown in the steamed treated soil had a 10% greater root diameter than the untreated control. There were treatment effects on marketable yields in trial 4.

Keywords: Steam, soil disinfestation, lettuce, carrot, spinach, soil-borne diseases

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Chapter 1: Literature Review

Introduction

Most crops are sensitive to weed competition during the early seedling stage of growth, which can ultimately reduce crop yield and quality (Fennimore et al., 2016). Weeds can also host many pathogens and insects, which can infect crops if left uncontrolled (Samtani et al., 2011). For example, an outbreak of wild mustard in a cabbage field can attract aphids. Large infestations of Johnson grass (*Sorghum halepense*) in a maize field can host maize dwarf mosaic virus, which allows it to overwinter in the weed rhizomes (Zimdahl 2018). Weeds can also compete with the crop by taking up plant nutrients and water by interfering with the crop roots by not allowing the crop plant grow to its desired size, leading to yield loss (Zimdahl 2018). High-density leafy green plantings can mitigate weed competition due to the extensive crop canopy cover, blocking sunlight from reaching the soil (Liu et al., 2019). In contrast, a low-density spinach crop can be severely infested by weeds because more sunlight can reach the soil (Liu et al., 2019). Greater light penetration to the soil can lead to more weeds germinating and becoming established creating complication and even difficulty in harvesting due to the weeds getting stuck on the harvester, resulting up to 20% crop loss (Liu et al., 2019, Zimdahl 2018).

Identifying weeds in a field seedbank can help guide weed management plans by knowledge of weed population pressure, seasonal weed germination patterns, life span longevity, and survival to understand the competitive advantage weeds have on crop plants (Liu et al., 2019). Uncontrolled weeds will reproduce and disperse their seed as much as they can before they die creating a seed bank (Radosevich et al., 1984). After seed maturity, seed dispersal occurs with the help of wind, water, animals, and humans (Zimdahl 2018). Eventually seeds end up in the soil, which allows the seeds to remain in a dormant state until favorable conditions allows seed germination. (Zimdahl 2018). Where annual weeds are allowed to grow and reproduce, they create a weed seed bank that varies by field and therefore can be difficult to control (Shem-tov et al., 2006). Lati et al., (2016) observed that weeds could impede crop development in the first four weeks of production. A farmer should know the weed seed bank in fields because the critical period to weed control can be based on the timing of emergence and weed management strategies can vary by season to determine crop choice and herbicide selection (Knezevic et al., 2002).

Weed management strategies can vary by crop but the ultimate goal is to reduce hand weeding and prevent loss of quality and weed contamination in salad mixes. For example, high-value crops, such as lettuce (*Lactuca sativa*) and spinach (*Spinacia oleracea*) are fast-growing; therefore, these crops can often be harvested before weed seeds can fully mature leaving little room of weeds to contaminate salad mixes (Tourte 2019). Weeds and weed seeds are very sensitive to their environment. In addition, fully mature weeds can detect short and long day lengths in order to set flowers and get ready to produce seed (Radosevich et al., 1984). For example, dandelion responds to short day lengths and can set large numbers of seed in the fall (Radosevich et al., 1984). Emergence of weeds like common purslane *(Portulaca oleracea)* emergence peaks in July when it loses light sensitivity, whereas burning nettle *(Urtica urens)* comes up throughout the year. The time of emergence peaks can vary by species and is crucial to know in order to make an effective weed management plan and prepare for future crop plantings.

With a few herbicides available for organic vegetable growers and few new herbicides being introduced for conventional crops, it is necessary to look for non-pesticide solutions. One area that appears promising is the non-chemical soil pasteurization method to manage weeds and pathogens (Fennimore 2016). In the late nineteenth century, steam pasteurization was developed as a method of soil disinfestation. Steam is injected into the soil to disinfest the soil from pathogens, insects, and weed seeds by maintaining 70 °C for 15-20 minutes (Newhall 1955). Treating an entire field with steam is expensive but strategic steam placement in bands is a way to reduce costs (Runia 2010). Band steaming can reduce the viability of weed seed in the bands that are treated where the crop plant will be planted. The effects of steam treatment can last for weeks or months. A study done by Runia (2010) showed that steam soil pasteurization can be part of an integrated program to manage some of the most troublesome pathogens like *Pythium.* spp. caused by pythium wilt and *Sclerotinia minor* caused by lettuce drop in lettuce production. Pythium wilt can be very destructive toward the end of the growing season affecting plant roots, and lettuce drop can cause total crop collapse affecting the lettuce crown. Soil disinfestation with steam appears to have potential, given the need for better control of pests in organic vegetable production in California. With continued research and further machinery improvement, it may be possible to reduce operating costs on a commercial scale by precision application of steam. This literature review will describe the latest advancements in steam to control pathogens and weeds for California vegetable production. Romaine lettuce, spinach, and carrots were chosen as the subjects of this study and will be discussed in detail. Treatments were steam and steam + hydrogen peroxide applied by 3 different steam applicators. Pests monitored were lettuce drop and pythium wilt, crop yields, and soil temperature, weed control and hand weeding times, were conducted in plots in the Salinas Valley. Steam application and the cost were evaluated.

Soil pests

Many soilborne pathogens affect vegetables; among them are *Pythium* spp., which weakens the roots of lettuce and *Sclerotinia minor,* which affects the lettuce crown and stems in contact with the soil causing them to breakdown, collapse, and die (Barriere et al., 2013, Subbarao et al., 2018). There is little new research regarding the efficacy of steam on pathogens in leafy crops. Some studies have stressed that *S. minor* and *Pythium* spp. are important pathogens with the potential to affect crop health in lettuce, spinach and carrot production (Barriere et al., 2013). Pythium wilt is caused by a fungal water mold that is most abundant in moist to wet field situations and can persist in the soil without a host and infect the roots of lettuce (Barriere et al., 2013, Subbarao et al., 2018). Spinach and lettuce are susceptible to the fungus under moist field conditions, which can result in total crop collapse (Wu et al., 2011, Mihuta and Rowe 1986). The pathogen develops in soil temperatures of 5 °C to 43 °C, with optimal temperatures of 20-24 °C that are common in a Mediterranean climate, such as California (Barriere et al., 2013). Depending on the environment, *Pythium* spp. can remain dormant in the soil for up to 8 years (Melzer et al., 1997, Caldwell et al., 2013). Pythium zoospores travel through the soil via water and causing infection, whereas oospores are survival spores that allow the pathogen to persist in the soil (Barriere et al., 2013, Subbarao et al., 2018).

Lettuce drop is a fungal disease known as white mold and lettuce drop (Caldwell et al., 2013). The pathogen is most abundant in moist field settings and has a broad host range including weeds and other vegetables (Caldwell et al., 2013). Lettuce drop affects the crown and stem of lettuce and persists in the soil as sclerotia that can last up to 8 years under dry conditions (Barriere et al., 2013, Subbarao 1998). The sclerotia are hard, black angular structures that can range in size depending on their developmental state but are smaller compared with *S. sclerotiorum,* which produce large smooth sclerotia (Barriere et al., 2013, Subbarao et al., 2018). Under environments favorable to *S. minor*, the lettuce plants will start showing white mycelium on the crowns of the lettuce (Caldwell et al., 2013). The pathogen grows in temperatures of 6 °C to 30 °C and 18 °C is the optimal temperature for this pathogen (Barriere et al., 2013). Lettuce drop is a serious problem in all lettuce production areas of the world and can cause crop losses up to 70% (Hao et al., 2003, Subbarao 1998, Hawthorne 1975). Pinel et al., (2000) evaluated the control of *S. minor* and *Pythium* spp. with a self-propelled steam applicator in a leafy vegetable trial in Italy. They found a significant reduction of both pathogens to a soil depth of 10 cm. A similar study done by Triolo et al., (2004) which was treated once and followed for 5 years, observed the steam treatment reduced *S. minor* by 68.6% after treatment.

Organic vegetable crops are valuable and weeds present a major risk to profitability, given the total value of high value crop production can cost up to $19,000 ha^{-1} (Smith et al., 2011). Some annual weed species can produce seeds more rapidly than others. For example, burning nettle (*Urtica urens)* can set seed in 45 days and thrive in a 65-day lettuce field (Fennimore et al., 2010). It is essential for organic growers to know the type of weeds that persist in their weed seed bank to know when to plant certain crops during the year. A worst-case scenario would be planting a high value organic crop in a severely infested weed field. For example, common purslane can remain viable in the soil for up to 20 years and a single plant can produce 52,300 seeds (Wilson 1988). In addition, perennial weeds such as yellow nutsedge (*Cyperus esculentus*) can live short or long lives and white clover *(Trifolium repens L.)* seed can persist 80 years or more (Wilson 1988).

Current Vegetable Practices

Over the years, horticultural studies and technology have been advancing. Olericulture is a branch of agriculture that relies on science to maintain profitable production in vegetable crops. Many of the 400 commodities produced in California consist of high value crops like almonds and lettuce (USDA 2020). In addition, these commodities are the products that make California one of the leading states in producing quality and high yielding specialty crops that boost

California's economy (USDA 2020). Profitable high value vegetable crops, such as lettuce and spinach, are not only a cool season and a quick maturing crop but are an example of some important crops that are grown nearly year-round on the Coast of California.

Lettuce

People discovered in the early 1900s, that the Coastal areas of California have favorable soils and a Mediterranean climate which is well suited for growing high value crops throughout the year (Griffin 1955). Currently, iceberg, romaine, and leaf lettuces are commonly grown (Tourte et al., 2019). Lettuce demand in the Western US increased during the 1930s, and the advent of refrigerated rail cars enabled the shipment of lettuce across the continent (Griffin 1995). While the industry benefited primarily from improved cooling facilities in the Salinas Valley and an accessible railroad, romaine and leaf lettuce became a popular crop by the 1950s that continues to be (Geisseler 2016). Lettuce is the 8th most important commodity produced in California and together with Arizona, these states produce 95% of lettuce in the United States, with a $3.1 billion farm value (CDFA 2020, Seaman 2016). According to the 2020-2021 USDA/NASS overview, there was a 22% increase in fresh market romaine lettuce production from 2019 to 2020, with Monterey County continuing to be the leader accounting for 61.9% of the state gross value total. Lettuce producers use transplants for some of the lettuce plantings, but most plantings are direct seeded into 40-inch beds with two seedlines or 80-inch beds that can have 5 to 6 seedlines (Smith et al., 2011). With higher density plantings, 2.5 inches of space are established between rows to ensure good spacing and to maximize yield (Chu et al., 2016). After the crop is established, it is thinned at the two to four leaf stage by a thinning machine to ensure crops are not too crowded (Chu et al., 2016). Consequently, thinning too much or too little can potentially affect the market quality of the product due to crop overlap or not having enough marketable plants to harvest. (Chu et al., 2016).

Spinach

The most common spinach types grown in California are fresh bunched, bagged spinach for salad mixes, and processed (frozen) (Koike et al., 2011). Four states grow 98% of spinach in the United States: California, New Jersey, Texas, and Arizona (USDA 2016). Most spinach produced in California is for the clipped and bagged spinach market, with California being the largest producer (Seaman 2016). Moreover, spinach is currently ranked the 23rd top commodity in California with a value of $281.8 million (CDFA 2020). The majority is grown in Monterey County, with 25% produced in Southern California and the San Joaquin Valley (USDA 2016). All commercial spinach producers grow hybrid spinach that is direct seeded at a high density on 80-inch-wide beds with up to 42 seedlines (Tourte et al., 2015, Koike et al., 2011., Seaman 2016). Spinach growers early on worked to ensure that there are no weeds present on bed tops because they use mechanical harvesters and have a very low tolerance for weeds, as they can contaminate packaged spinach (Lati et al., 2016).

Carrot

Carrots grown in California have a fresh market value of $643 million greater than other carrot-producing states like Michigan and Texas (CLF 2012). As stated by the Crop Protection Research Institute, carrots are primarily grown in the Cuyama Valley, Kern, and Santa Barbara County areas and California production accounts for 85% of fresh market carrots in the United States (CLF 2012). A disease that causes significant damage is carrot blight caused by *Alternaria dauci,* which can weaken the tops of the crop which are needed for mechanized harvesting. Therefore, farmers rely heavily on fungicide sprays and is the reason why only 10% of farmers grow carrots organically (Du Toit et al., 2014, Nunez 2008). Carrots are grown at high densities just like spinach, which makes cultivation difficult. Weeds can also be a problem by clogging machine harvesters (Nunez 2008). Carlesi (2021) argues it is important that weeds are controlled during the early stages of carrot growth. Competition from weeds can reduce yield and because the crop canopy is not as dense, it can allow light penetration through the canopy, which can encourage additional weeds to emerge (Nunez 2008). Organic growers have few pesticides to control weeds and diseases. In addition, treated carrot seeds are used and are always seeded into the soil on 40-inch beds each with a total of six to eight rows (Carlesi 2021). In addition, carrots are mostly started by sprinklers and then switch to furrow irrigation to prevent the spread of carrot blight and bacterial blight (Du et al., 2014). Other diseases like *Pythium* spp. can also affect the crop in the early seedling stages causing early die off due to wet soils where overhead irrigation is used and later by causing cavity spot, which can result in major economic losses (Carlesi 2021).

Current Pest Control Practices

It is essential to use physical, cultural, and chemical control practices to ensure good weed and pest control (Fennimore et al., 2010). Current circumstances have made incorporating these concepts in the field challenging. For example, spinach, lettuce, and carrot are often grown at high densities with little space for cultivation (Lati et al., 2016). Integrating a pest management plan can vary among farmers and that can depend on type of crop grown, field location and field history, resource availability, and cost.

Cultural control

Cover crops are used to not only trap soil nutrients and prevent it from leaching, but also to control weeds (Liebman and Davis 2000). Cover cropping works by quickly adding a crop and covering the soil to prevent weed establishment (Nelson 1991). In addition, using cover crops to control *Pythium* spp. in a 3-year interval can be effective because of improved soil fertility and its ability to suppress pathogens (Shem-Tov et al., 2006, Shennan et al., 2018). Rotations with broccoli are very effective because once the crop residue is broken down in the soil it produces glucosinolates that can suppress pathogens (Hao et al., 2003, Kim et al., 2021). In addition, grain crops can also be effective, but legumes have poor performance in suppressing pathogens (Caldwell et al., 2013). Pathogen distribution can be influenced by irrigation and poor water drainage (Kiehr et al., 2015). There needs to be enough water for the zoospores of Pythium for successful infection and spread to other parts of the field (Mihuta and Rowe 1986). Pythium wilt primarily infects below the ground, causing roots to decay and turn gray and brown, causing damping-off in early plant development (Mihuta and Rowe 1986). A study by Pinel et al., (2000) was able to control *Pythium* spp. with steam 90-99% of the time in the first 5-10 cm of the soil and observed it did not recolonize during the 3-month trial duration.

Prevention of weed seed maturity is necessary to reduce replenishment of the seedbank and cultural management of some weeds after crop harvest is crucial since weeds have already dispersed their seeds into the soil (Pekrun 1997). Tillage immediately following harvest will minimize weed seed set (Pekrun 1997). In addition, inadequate rotation programs, and continuous planting of lettuce can cause a reoccurrence of common purslane *(Portulaca oleracea)* in the soil, especially because it can reroot in the ground and can continue to grow (Fennimore 2013). Because crop rotations allow use of different weed control means, broccoli would allow use of oxyfluorfen (GoalTender®) post emergence herbicide in a integrated pest management (IPM) program to control purslane, but growers do not make money on broccoli which is why they stick to growing lettuce and grow broccoli when they have to.

Crop and weed competition are always at play and all control measures must be used to help the crop to out compete the weeds. The key to weed control is to act early to prevent weed establishment and promote crop competition with weeds. Integrated weed management takes advantage of the crops larger size, such as transplants and cover crops that can rapidly cover the soil surface. The transplants have the ability to establish earlier than the weeds (Bond et al.,1998). High density cover crops suppress weeds, and high density lettuce help suppress weeds, although cultivation and weed removal is difficult (Bond et al., 1998, Odero 2013). Understanding weed seedbanks and integrating an ecological-based approach to weed management will allow growers to develop better weed control programs (Roberts 1981). These weed control programs can be improved in the future by looking at seed dispersal and emergence in terms of species and creating models of competition to better plan a weed field site program (Albrecht and Sommer, 1998).

Using living mulches can also aid in suppressing weed germination due to its ability to prevent light transmission into the ground and its ability to control the temperature of the soil (Teasdale 1993). In addition, the cover crop can serve as an added allelopathic affect, which can also aid in impeding weed development and germination of annual weeds, but allelopathy is not a dependable tool since it is variable (Liebman 2000). Another pest management practice that is used is intercropping. This involves rotating crops and controlling weeds at the same time, resulting in yield increases (Locke et al., 2002). While using crop rotations to control weeds is effective, allowing fields to be fallow can also be of great benefit (Blake 1990). When dealing with fast maturing crops, the grower can prevent weeds from dispersing seeds (Turner 1999). Since weeds adapt to continuous use of the same tools, implementations of other integrated management plans are crucial (Rasmussen 1993).

Hand weeding

Using more than one management strategy increases the probability of weed control success like implementing a form of physical control like hand weeding integrated with herbicides can control weeds (Bond 2001, Rasmussen 1993). In the produce industry 42% of total weed control expense is due to labor costs (Calvin 2010). Organic vegetable farmers are extremely limited in the choice of registered herbicides they can use, making it necessary for growers to explore more options to manage weeds (Fennimore 2001). California passed legislation in 2016 that increased the minimum wage by a $1.00/hr. per year until it reaches $15.00/hr. in 2022 (Tourte 2019). With this change in place, the agricultural industry will face higher labor costs (Tourte 2019). Costs associated with hand weeding, in general, are between $300-$700 per hectare, which has continued to increase in prices as much as 64% in the last ten years (Lati et al., 2016, Tourte et al., 2019). Because there are few herbicides for lettuce production, hand weeding labor costs will get even higher (Fennimore et al., 2016).

Tillage and cultivation

Tillage combined with herbicides can be an effective integrated treatment method (Cordeau et al., 2017). Seedbeds that are frequently cultivated will generally have higher weed populations, leading to more weed outbreaks (Bond 2001). When dealing with soil that is cloddy the weeds are protected by the clods of dirt and need to be broken down further when prepping a field for crop seeding (Bond 2001). Using a mechanical weed cultivator in a high-density spinach field can cause crop injury, which is why spinach must be hand-weeded (Fennimore 2016). There are drawbacks when it comes to mechanical cultivation (Fennimore 2016). Studies have shown that even the more advanced weeding machines have a hard time removing weeds close to crop plants (Fennimore et al., 2010). Intelligent robotic weeders are another method currently being implemented, but these can be challenging to use in high density crops and wet conditions (Blasco 2002). Even with more advanced machines available, these robotic weeders are expensive and only the larger growers can adapt to the technology and afford high fixed costs while small growers struggle to invest (Calvin 2010). Some cultivators can only control small weeds, but it is challenging to take out older, deep-rooted weeds in lettuce production (Lati et al., 2015). In conclusion, cultural, physical, and chemical control methods cannot be separated and work best when used together in an integrated pest management plan.

Organic and Conventional Vegetable Production

Organic demand

Organic agriculture is a sustainable production system that considers long-term effects involving preserving biodiversity, soil health, and the environment. There is a growing demand for organic vegetable crops for consumers who don't want to be exposed to pesticide residues, especially on food for children (Gaskell 2000). Organic certification is a stringent process that allows food to be sold as organic (Tourte 1998). While the demand for organic produce continues to increase, it's challenging to find effective ways to manage soil pathogens and weeds with few good pest control tools. Some challenges include high weeding costs because there are few organic-compliant herbicides, and effective management of soil pathogens is difficult. Research in weed and pathogen management for organic systems is not a high priority for many researchers and does not receive much attention, especially in production dealing with high yielding produce crops in an ever-growing marketplace (Runia 2010). There is constant worry about persistent weed infestations in organic agriculture due to many weed escapes (Bond 2001). In organic leafy crop production, there is a couple strategies they can use to control persistent weed infestations, one way to reduce surface seed bank is by deep burial. This method is called plowing, which involves incorporating weed seeds into the ground, which prevents weed seeds from germinating (Hartmann and Nezadal 1990). Plowing can create a problem because it involves burying weed seeds deep into the soil and will eventually be brought back to the soil surface during future field cultivations, so other organic production methods should be incorporated (Hartmann and Nezadal 1990). The timing and depth of cultivation can have an effect on different weeds in a seedbank (Hartmann 1990). Some weeds depend on light in order to germinate and is why weed seeds can be viable for so many years when buried deep into the soil where they are not exposed to light (Hartmann 1990). Farmers have adapted to increased food production using intensive land cultivation during the green revolution and saw how productive and efficient it was to produce crops (Barriere 2013, Oatsvall 2014). Yet, extensive land cultivation can create more problems if not planned accordingly, so farmers learned how efficient it was to grow crops in rotation after harvest as another strategy to control pathogen inoculum and weed seeds in the soil as a common practice in organic production (Dabbene et al., 2003). Some organic practices that are used in lettuce production in coastal areas of California are crop rotations with mustard family species, into their integrated pest management program to help enhance soil fertility in an area of extreme soil disruption (Barriere 2013). Rotational crops are planned months before planting, and farmers need to have high returns to offset land and high production costs with greater risk of aphids and diseases in organic production (Klonsky 1994).

Conventional agriculture

In spinach production, the most common herbicides used are phenmedipham (Spin-aid®) and cycloate (RoNeet®) (Fennimore, 2001). These herbicides control grasses and broadleaf weeds, but they only control 2 out of 5 important weeds (Fennimore, 2001). Phenmedipham can be used at the three true leaf stage of spinach but often cause crop injury for a short period and is labeled for processed spinach in California (Lati 2016). Therefore, growers need to know their weed seed bank to determine what methods would work best in their weed management plan. For preplant fumigation, which involves applying a product such as Metam sodium before the spinach is planted (Fennimore 2001). However, Metam sodium is not preferred because it is restricted and has a 14-day wait before planting (Fennimore 2001). Cycloate is the main preemergent herbicide used after seeding but before emergence and can also be pre-plant incorporated into the soil (Lati 2016).

In lettuce production, herbicides like Benefin is also used as a preplant herbicide applied with the help of machine incorporation on the tops of lettuce beds (Smith et al., 2009). Using this herbicide comes with precautions because it can persist in the soil for months and can affect rotational crops like spinach, onion, corn, and sugar beets (Smith et al., 2009). Incorporating the herbicide too deep can result in poor weed control (Cudney 2002, Smith et al., 2009). Bensulide (Prefar®) is an important lettuce preemergence herbicide that controls annual grasses but is weak on pigweed (Smith et al., 2009).

Pronamide (Kerb®) is the most common preemergence herbicide for lettuce organically registered in 1969 (Smith et al., 2009). The herbicide does not need to be incorporated into the ground (Smith et al., 2009). Kerb provides excellent control of grasses and weeds in the mustard family (Smith et al., 2009). In addition, Kerb partially controls goosefoot and purslane in the nightshade family, malva and pigweed does not control weeds in the sunflower family like common sowhistle (*Sonchus oleraceus*) and common groundsel *(Senecio vulgaris*) (Smith et al., 2009). Many growers have trouble with Kerb, especially in Yuma, Arizona because it leaches too deep in the soil profile when lettuce is irrigated, causing poor weed control (Smith et al., 2009). In addition, Kerb is a possible human carcinogen and has been found in groundwater (Smith et al., 2009).

In today's herbicide market, herbicides have been regulated and banned, leaving those that are more than 40 years old and subject to cancellation in the future (Smith et al., 2009). Cycloate and Dual Magnum are the only pre-application products in the market that can be used in spinach production, but Dual Magnum is not used much (Smith et al., 2009). Lati (2016) stated Cycloate controls broadleaf weeds well but can be difficult to control weeds in warm conditions due to increased volatility and loss. Growers continue to use herbicides because it benefits them by reducing the number of weeds in the field. Therefore, it requires less labor to hand weed in leafy crop production. Dual Magnum, an herbicide that was registered in 1977 and has a pre harvest interval timing of 50 days and is too long because spinach can be harvested in as little as 25 days (Smith et al., 2009). In addition, Fennimore (2013) argues that weeds like purslane can be problematic and thrive under heavily cultivated soils and in Salinas Valley's Mediterranean climate. When herbicides like Pronamide (Kerb) and Bensulide were introduced in the late 1960s, there was an improvement in control (Fennimore, 2013). However, growers continue to have problems where reoccurring purslane infestations are persistent (Fennimore, 2013).

Developing a new herbicide can be very difficult and expensive. The process takes 9 years and involves studying the environmental impacts of the chemical and proper development and rigorous field trials before it can be registered to be used. Sometimes chemicals going through this process do not make it successfully. Other alternatives to control weeds include using biotechnology to make herbicide-tolerant lettuce. Fennimore (2003) found that using glyphosate tolerance lettuce could control weeds better than Bensulide and Pronamide. In general, it can be costly to take this type of biotechnology to a commercial scale, but the lettuce industry soundly rejected roundup ready lettuce before it was introduced.

Steam Application Methods

Steam application to the soil is a method to disinfest soils by killing pathogens and weed seed in the soil. The concept of heating the soil started in greenhouse flower production dating back to the 1800s and even as far as ancient times (Newhall 1955). Steam disinfestation first came into use in the United States in 1893 to treat greenhouse pots and eventually, as technology started evolving, different types of machine steamers were created (Newhall 1955, Luvisi et al., 2008). For example, mobile steamers come in tractor-towed or self-propelled models. Several different types of steaming techniques have been developed and evaluated in terms of costs and pathogen and weed suppression (Baker 1962). The average cost of steaming was $4,883.24 an acre compared to the cost to use chemicals like methyl bromide or 1,3 chloropicrin application that would cost $7,324.86 per acre (Luvisi et al., 2008). Extensive research on the efficacy of steam opened new opportunities for improved steaming techniques in greenhouse production (Samtani et al.,2011). Steam was used widely in the 1950s and 1960s, but in the 1970s, high fuel costs made steam more expensive than fumigants and so greenhouses switched to fumigants like hot gas methyl bromide (Samtani et al., 2011, Langedijk 1959). With increased chemical use regulations in greenhouse and field settings and the loss of methyl bromide, growers have renewed interest in steam.

Chemical fumigants came into use in the 1960s when farmers soon found fumigants to be a cheaper and more efficient way of killing weeds and soil pests than steam (Runia 2010). However today, it is difficult and expensive to use chemical fumigants in California agriculture due to strict regulation. Steam on the other hand, provides an alternative and is not regulated

(Samtani et al., 2011). Many argue steam is a viable alternative to methyl bromide, but better steam application methods and applicators are needed (Fennimore et al., 2013). One concern about using steam disinfestation is overheating the soil, killing beneficial microbes key in soil nitrification (Fennimore 2013, Gay et al., 2010). Wherever steam is used, steam needs to reach a temperature of 60-70 °C for 20-30 mins dwell time to control soil pathogens and weeds effectively (Kim et al., 2021). Because romaine lettuce and spinach are shallow-rooted crops grown in rows, the depth of steam injection application using a banded steam technique is set to 19 cm or shallower in depth (Kim et al., 2021). When applying steam to moist soils, the following temperatures are set to kill the organisms in increasing order in 30 mins durations (Figure 1; Baker 1976):

Figure 1: Temperature ranges that kill organisms (Baker 1976).

Temperatures	Organisms
49°C	water molds
63- 71°C	invertebrate pests such as snails, slugs, bacteria, and fungi
82°C	weed seeds
100°C	virus and weeds that are heat resistant

Studies done by Baker (1957) and Van Loenen et al., (2003) evaluated the effects of various temperatures and exposure times on soil pathogens by soil type using dry steam. Dry steam is created by generating steam with one pass through the boiler followed by a second pass so that the temperature is higher and there are no water droplets (Baker 1957). Baker (1957) found that when steaming soil in pots that were dry at a lower temperature, it took longer to reach the appropriate temperature to kill soil pathogens. In contrast, Baker (1957) also observed that when potted containers were moist just before steam application and steamed at a higher lethal temperature dose for 30 mins he observed higher kill rates of soil pathogens.

Sheet steaming is one of the oldest methods of steam application and is still used in greenhouse production (Runia 2010). The downfall of this technique is that the steam process takes 8 hours, and the performance of steam is better in clay soils, according to a study done in Italy by Gay et al. (2010). To heat the deeper layers of the soil takes long to reach the appropriate temperature to kill soil pathogens but gave the best results in steaming the top 15 cm of the soil (Gay et al., 2010). Sandy soils were the most challenging soil type to steam with this method (Gay et al., 2010).

Raffaelli et al., (2016) used a steaming machine that uses a negative pressure steam technique that involves applying steam to the top 10 cm of the soil underneath a tarp into the soil. A fan is also used creating suction through polypropene tubes buried in the soil (Raffaelli et al., 2016). The negative pressure technique used 50% less fuel than traditional sheet steaming (Raffaelli et al., 2016). The negative pressure technique does a better job in achieving greater steam temperatures in the lower layers of the soil (Runia 2010, Raffaelli et al., 2016, Gay et al., 2010). In contrast, the sheet steaming technique does a better job in steaming the top layers of the soil but often overheats the soil killing beneficial microbes (Runia 2010, Raffaelli et al., 2016, Gay et al., 2010). New steam machines have incorporated steaming hoods that are moveable where pipes are put directly into the soil and treat smaller areas and do not involve covering the soil with sheets (Pinel 2000).

Raffaelli et al., (2016) observed increased carrot yields after steaming and it reduced weed competition during the first 45 days based on weed dry biomass at harvest. Raffaelli et al., (2016) also observed 90% weed control at 30 DAT and 70% weed control at crop maturity. Another study done by Fennimore et al., (2014) observed a 25% to 93% time reduction in hand weeding time in strawberry when a temperature of 70 °C was held for 30 minutes. After steam application the temperature peaks and then there is a steady decline in soil temperatures (Melander et al., 2005, Pinel et al., 1999). Co-application of exothermic compounds with steam helps maintain the temperature at critical temperatures for a longer period with better pest efficacy (Luvisi 2006, Luvisi 2008, Pinel et al., 1999). Studies done in Sweden and Norway saw slow declines in steam temperatures that dropped from 100 °C to 60 °C in a matter of 2 hours and that is due to using an older steam machine (Pinel et al., 1999). There needs to be greater steam penetration in the soil to ensure that soil aggregates are targeted, and the critical temperature dwell time are realized (Melander et al., 2005).

Band Steaming

Applying steam in bands centered on the seedline is an efficient method of placing steam only where it is needed. Melander et al., (2005) found that using band steaming lowers energy consumption by only steaming in bands where the seedline will be located. Banded steaming is the most favored application technique and has been used recently in strawberry and lettuce production (Melander et al., 2005). Weed emergence was evaluated after banded steam application and resulted in a 30% reduction in hand weeding time in the intra rows of the bed (Raffaelli et al., 2016). Steam controls weeds in the band closest to the crop where it is most difficult to control weeds. The weeds that are in the intra row space outside the bands can then easily be removed by a cultivator (Lati et al., 2015, Melander et al., 2005).

A study performed by Fennimore et al., (2016) found that mobile steaming is more favorable than stationary steaming because it is easier to control the soil temperature by adjusting the speed of applicator and the ability to move with minimal labor input. In addition, steam involves no worker exposure to fumigants (Fennimore et al., 2016). Melander et al., (2005) and Pinel et el., (1999) stress the point that there is not much research done on mobile steaming in field settings, given the great need. The mobile steamer used in the Melander et al., (2005) study has been used commercially and is close to the type of unit used in my 2020 spinach trial: the Steamy (Korean steamer) (Figure 2). It uses a rototiller to incorporate steam through shanks into the soil at about 1.6 m wide and 20 cm deep (Fennimore et al., 2016).

Figure 2: Steamy (Korean steamer).

Moreover, there have been studies looking at the amount of energy that is used by steam machines and Van Loenen et al., (2003) controlled major soil pests at a lower energy state using aerated steaming at a lower temperature of 50-60 °C in 11 minutes but was done in a laboratory setting. More banded steam studies need to be conducted on a larger field scale that mimics a commercial production with a natural disease population in the soil. More research needs to be done to improve steam generator systems and efficacy in soil steam incorporation while using less fuel and maintaining the proper dwell time (Melander et al., 2005). The goal for steam use is explained in high-value cropping systems as a technique used in integrated pest management programs to reduce the abundance of harmful soil pests with little effect on the biology of the soil by disinfesting the soil before planting the crop (Luvisi et al., 2008). The process uses water vapor to transfer the heat from a heat source to the soil (Kim 2021). Furthermore, when the water vapor is injected into soil and comes into contact with the cooler soil particle, then steam condenses and transfers the heat energy to the soil with the goal of reaching critical temperatures. Pathogens on or near the soil particles are controlled by the lethal temperatures (Kim et al., 2021). In addition, steam disinfestation will benefit organic growers and help those that have fields near sensitive sites like schools where strict regulations are put in place and chemicals cannot be applied (Kim et al., 2021). This will ultimately help with net revenues, increase yields, and reduce risk of economic loss to soil borne diseases (Fennimore et al., 2016).

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Chapter 2: Banded Steam for Weed and Disease Control

Introduction

Vegetable crops have been grown commercially in the Coastal areas of California since the early 1900s. These areas have fertile soils and a Mediterranean climate favorable for high value vegetable production year-round (Griffin 1955). Various types of romaine lettuce, carrot, broccoli, and spinach are commonly grown vegetables in Coastal California (Tourte et al., 2019, Griffin 1955). Farmers have traditionally managed weeds by hand weeding, but are currently facing a labor shortage. Workers are not always available when needed. Crops can have multiple flushes of weeds depending on the weed seed bank in a given field during the growing season (Fennimore et al., 2016). High density lettuce crops are often weedy in the intra row space close to the crop where the weeds are difficult to remove with a cultivator. This leaves hand weeding as the best option (Odero 2013). Leafy greens are grown intensively and continuously, often on the same land after each harvest throughout the year (Fennimore 2016). Weed management in organic vegetable fields is even more difficult than conventional fields. Organic producers have few good weed control tools and new weed control options are needed (Fennimore 2001). It is essential to use physical, cultural, and chemical control practices to develop an integrated pest management plan to avoid pest resistance and ensure good weed and pathogen control (Fennimore et al., 2010). Current circumstances such as increased labor, hand weeding costs, and lack of new herbicides threaten profitability and clearly there is a need for more pest control options.

Hand weeding costs are increasing, partly due to California legislation in 2016 that increase the minimum wage by a $1.00 per year until it reaches $15.00 in 2022 (Tourte 2019). The agricultural industry will suffer because farmers will pay their workers more especially in labor intensive crop systems (Tourte 2019). Crop and weed competition are a constant struggle and the crop needs to be protected from weeds and the earlier it is done, there is less of a chance of crop loss to weeds (Bond et al.,1998).

In the late nineteenth century, steam pasteurization was developed and used to inject steam into the soil to eliminate soil pathogens, insects, and weed seeds (Newhall 1955). Steam soil pasteurization is a physical method that controls some of the most troublesome pathogens like *Pythium* spp. and *S. minor* in lettuce production (Runia 2010). Old methods like sheet steaming applied steam to the entire soil profile and resulted in high fuel consumption (Langedijk 1959). To reduce costs, prototype band steamers were developed to target steam into narrow strips of the soil carefully positioned where the seedline will be located after steam application (Pinel et al., 2000). Mobile band steaming may be the best option for pest control in the seedline (Baker 1962, Luvisi et al., 2008).

Amendments in combination with steam may improve steam efficacy by increasing temperature dwell time in the soil and result in better weed and pathogen control (Kim et al., 2021). Hydrogen peroxide (H_2O_2) is an organic-compliment antiseptic that can kill harmful fungi and bacteria (Perchonok 2005). Hydrogen peroxide is a naturally occurring molecule commonly used to disinfect foods and is water-soluble and decomposes quick with no residue left after application. Importantly, this chemical can create an exothermic reaction in the soil, in theory enhancing steam by increasing soil temperature when co-applied (Abdollahi 2014). Hydrogen peroxide continues to be a unique and useful amendment used in food processing plants that has much potential to be studied more extensively in high-value production with different steam applicators.

The objectives of this project were to evaluate pathogen and weed control efficacy of steam applied in a band prior to planting vegetables. An additional objective was to evaluate steam + hydrogen peroxide applied as a band to determine whether this product improves the pest control efficacy of steam.

Materials and Methods

Steam trials

Two lettuce trials were conducted in 2020 and one in 2021. A single spinach trial was conducted in 2020 and a single carrot trial in 2021. With the exception of the spinach trial, all trials utilized a band steam applicator. In the spinach trial, a self-propelled steam applicator was utilized (JSE, Daegu, Republic of Korea; Figure 3). Thus, three field trials were conducted in 2020 and two were conducted in 2021. The 2021 lettuce and carrot trials were performed using a banded steam machine developed by the University of Arizona at the Yuma Agricultural Center. For all trials, the steam applicator used softened water that was obtained from a Culligan Water softener. Critical trial events and dates can be found in Table 1. The site location for all trials was at the UC ANR Hartnell Research Station in Salinas, California. The soil type is a loam composed of 53% sand, 32% silt, 15% clay and with 2.09% organic matter. The electric conductivity of the soil is 1.65 with a pH of 7.03. Soils in all five trials were checked for abundance of *Pythium* spp. colonies and *S. minor* sclerotia before starting the trials. Soil samples were taken from all plots before and after steaming to measure efficacy on pathogen populations. Honest Observer By Onset (HOBO) temperature recorders (Onset Computer, Bourne, MA) were used to monitor soil temperatures during the steaming process and were left in the soil for 24 hours after steaming.

Figure 3: Steamy (Korean steamer) photo courtesy of Steve Fennimore.

Table 1: Critical dates for all trials

Experiment/Crop	Preplant/Steam	Planting	Weed density measurements	Yield evaluations
1. Lettuce	Jul 1, 2020	Jul, 2	Jul 13, 27	Sept, 31
2. Lettuce	Jul 21, 2020	Jul, 22	Aug 6, 24	Sept, 25
3. Spinach	Oct 26, 2020	Oct, 27	Nov 6, 13	Jan, 13
4. Lettuce	Jul 9, 2021	Jul, 12	Jul 26, Aug 9	Sept, 22
5. Carrot	Jul 8, 2021	Jul, 9	Jul 26	Oct, 01

Lettuce trial 1 and 2 consisted of 6 beds, 105 ft long by 3.33 ft wide plots. A bed shaper equipped with 4 shanks injected steam in a band, 3 inches deep by 4 inches wide, connected to a 20 BHP steam generator (Sioux, Beresford, SD) used to supply steam at 6 to 9 PSI centered on where the lettuce seedline was to be located (Figure 4). A 13.5 m x 1.7-m rubber insulator was towed behind the bed shaper to hold heat in the soil longer. The steam implement was towed by a 5520 John Deere tractor that was set at a constant 2,000 RPM, moving 8ft per minute while steaming. Trial 1 was steamed on July 1st and direct seeded only July 2nd 2020. Trial 2 was steamed on July, 21st and direct seeded on July 22nd 2020. Both trials were planted with a Stanhay belt planter that utilized 2.25 in-line seed spacing for 1 seedline. In combination with steam, Organic Materials Research Institute (OMRI) labelled 35% concentrated hydrogen peroxide was applied at 105 gal/acre through a nozzle at 40 PSI aligned with the lettuce seedline. Treatments included were steam alone, steam + hydrogen peroxide and no steam as a control. Treatments were replicated 4 times and arranged in a randomized complete block design. Data recorded in all 3 trials were weed densities at 2-week intervals, disease incidence, temperature, time of hand weeding, lettuce diameters and crop harvest yields.


Figure 4: The bed shaper used as a steam applicator in 2020.

In spinach trial 3, the Steamy applicator was utilized, which is only able to treat flat ground. Thus, raised beds were not used in this trial. Each plot was 5 ft wide by 20 ft long. A JSE self-propelled broadcast steamer applicator that is 14 feet long and 6 feet wide from Korea was used on flat ground. The machine is self propelled and physically mixes the steam with the soil as it passe through the ground. Treatments were replicated 6 times and arranged in a randomized complete block design. Treatments were steam alone and a non-treated control. The spinach (Merrak Rz F1) variety was direct seeded 2 DAT on October 28th 2020 using a high density, 8 line, 40 inch wide seeder attached to a John Deere 5520 4WD. In addition, the planter dispersed 1.5 seeds every 13.6 seconds.

During the summer of 2021, lettuce trial 4 and carrot trial 5 consisted of 8 beds. The lettuce trial plots were 180 ft long by one single bed 3.33 ft wide, whereas the carrot trial was 120 ft long by one bed wide. A prototype field steam applicator from the University of Arizona with a 35 BHP Clayton Sigma Fire (Clayton Industries, City of Industry, CA) generator equipped with a bed shaper with shanks that injected steam in a band, 4 inches deep by 4 inches wide centered on where the crop seed line was to be located (Figure 5). The steam applicator was attached to a 5520 John Deere tractor and was set at 2,000 RPM, moving 8 ft per minute during steaming. The lettuce (Green Towers) variety was direct-seeded 3 DAT on July 12th 2021 and the carrot (Morelia) variety was seeded 1 DAT on July 9th 2021 in all plots. Both trials used a Stanhay belt planter that utilized 2.25 in-line seed spacing for 2 seed lines for the lettuce trial and scattershoe for the carrot trial that dispersed the carrot seeds in a 3-inch band. Treatments were steam alone and a no-steam control. Treatments were replicated 4 times and arranged in a randomized complete block design. Data recorded in both trials were weed densities at 2-week intervals, disease incidence, temperature, time of hand weeding, lettuce canopy diameters and crop harvest.


Figure 5: Clayton Steam applicator from Yuma, Arizona.

Pathogen populations in the soil

Soil samples were taken from the top 15 cm of the soil for determination of the abundance of *Pythium* and *Sclerotinia*. Naturally occurring populations of *Pythium* spp. and *S. minor* were determined before and after steaming in all plots. For *Pythium* spp, 2 soil samples from each plot were collected before and after treatment for all trials. For the samples collected, 500µL of the sample solution was pipetted and evenly spread onto five petri dishes that contained Difco Corn Meal Agar (CMA) and replicated 6 times. In addition, 500µL of sample solution from the spinach trial were spread onto 5 petri dishes and replicated 3 times. Petri dishes were stored in a dark room at 21-24°C degrees and the number of Pythium colonies were counted 24 and 48 hours later and documented (Figure 6) (Klose et al., 2008).

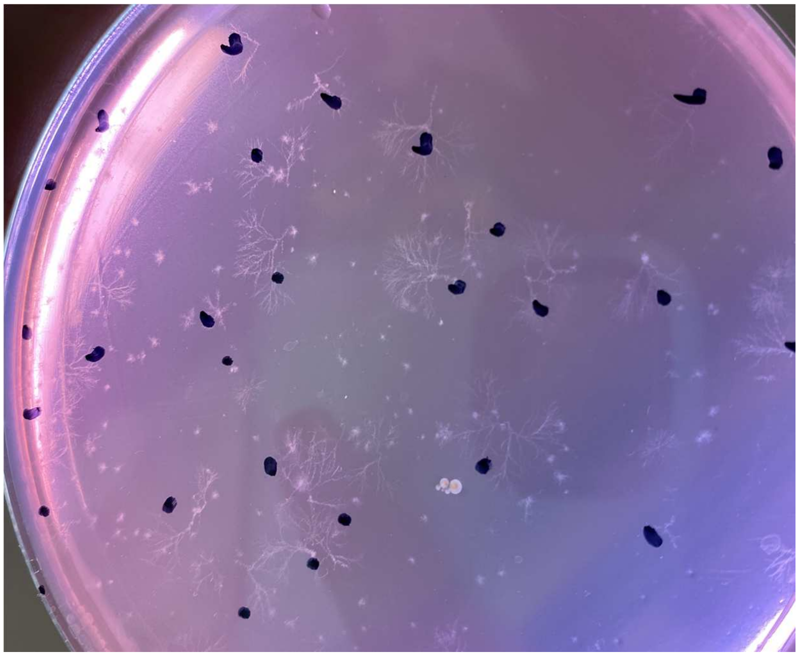

Figure 6: *Pythium* spp. colonies 24 hours after inoculation.

To measure the abundance and recover *S. minor* from all trials, 2 soil samples were taken from each plot and 100 g of soil was sieved through a 300 mm and 2 mm sieve. The remaining soil was put in an Erlenmeyer flask and 100 ml of 2% Calgon solution was added. After 5 minutes, this solution was mixed with 1000 ml of tap water and put in another Erlenmeyer flask that had a coffee filter inside of a funnel placed over the top of the flask to separate the sclerotia from the organic matter and soil debris. Sclerotia were counted after extraction under a microscope from the coffee filter (Figure 7).

Figure 7: Examples of *Sclerotinia minor* sclerotia that were found.

Weed densities

Weed densities were measured at two-week intervals in a 0.5 ft^2 sample area at the same locations in the steamed banded area for all trials. The total weed abundance by species was determined in all treatments and two subsamples were collected from each plot for the lettuce trials. For lettuce trial 1, weed densities were measured at 12 and 26 DAT in a single seedline. For lettuce trial 2, weeds were counted 15 and 33 DAT as well. For the lettuce trials, subsamples were taken in each plot and the 4 most abundant weeds were documented. For spinach trial 3, the number of weeds were counted 19 DAT in all 8 seedlines and the 4 most abundant weeds were documented. Treatment effects were observed and were compared to the control. Weeds were counted and collected in all plots in the spinach trial at harvest. For lettuce trial 4, the number of weeds were counted at 17 and 30 DAT in both seedlines and the top 4 weeds were documented. In addition, the number of weeds counted was conducted 17 DAT in both seedlines and the top 4 weeds were documented.

Diseased plant counts

Plant stand evaluations were conducted by counting the number of healthy and diseased plants in a 30 ft portion of bed. For lettuce trial 1, evaluations were counted on 7/20/20, 8/5/20, 8/19/20 and 8/26/20. For lettuce trial 2, evaluations were done 8/7/20, 8/20/20, 9/3/20 and 9/16/20. For the 9/16/20 evaluation, the sample size was increased to number of plants in a 105 ft portion of bed, because this was more representative of abundance of diseased and healthy plants in the plot. For spinach trial 3, the number of healthy and diseased spinach leaves in 5 ft of bed were counted on 11/09/20 and 11/26/20. For lettuce trial 4, the number of healthy and diseased lettuce plants in a 30 ft portion of bed were counted on 7/29/21, 8/11/21, 8/25/21 and 9/08/21. For trial 5, the number of healthy and diseased carrot tops in a 5 ft portion of bed were counted on 7/26/2, 8/11/21, 8/25/21, and 9/08/21.

Duration of soil temperature

To monitor the temperature of the soil after steaming, HOBO (Onset Computer, Bourne, MA) data loggers were used to measure soil temperatures at a depth of 10 cm in all treatments in the treated band for 24 hours after steaming. The temperature probes were installed immediately after the steam applicator passed.

Measurement of hand weeding time

The areas around the lettuce and carrot crops were weeded by a worker with a hoe and hand pulled as needed. Timed weeding was done before and after mechanical cultivation on 10 ft of bed in all blocks for all trials before and after cultivation except for trials 3 and 5. Timed weeding for spinach trial 3 was on 5 ft of bed. All 8 seed ines of the spinach trial were weeded by hand. For carrot trial 5, timed weeding was only done before mechanical cultivation on 5 ft of bed. The process was done to ensure a good representation of weed control in a commercial field.

Harvest

For all lettuce trials, the weight, size and number of marketable mature heads were collected per 10 ft^{-1} of bed at harvest. For the spinach trial, 5 ft^{-1} (8 seedlines) of marketable spinach leaves was harvested and weighed and tons/acre was calculated. For the carrot trial, the weight, size and number of marketable mature carrots were collected per 5 ft^{-1} of bed.

Crop canopy: (perimeter)

Crop canopy diameters were measured at 41 DAP for lettuce trials 1, 2 and 4. Crop diameters of 20 plants per plot were measured from the outermost leaf from one side to the outermost leaf on the other side with the ruler on the soil surface of the lettuce plant and were averaged.

Statistics

Analysis of variance (ANOVA) and mean separation was performed using LSD's using R Studio and Agricultural Research Manager. Levene's test of homogeneity of variance, and t-tests were done in R Studio.

Results

The time above 70 °C in the steam alone treatment for trial 1 was 88 minutes and 76 minutes in the steam + H_2O_2 treatment (Table 2). The time above 70 °C in the steam alone treatment for trial 2 was 67 minutes respectively, and 80 minutes in the steam + H_2O_2 treatment, respectively (Table 2). Trial 3 temperature above 70°C was kept the longest out of all trials in the steam alone: 176 minutes at 10 cm depth compared to the control. The temperature above 70°C in trial 4 was 98 minutes at 10 cm in depth compared to the control (Table 2). Trial 5 temperature for the steam alone treatment above 70 °C was 105 minutes at 10 cm depth compared to the control (Table 2).

Table 2: Duration of soil temperature for one hour after steam application at three temperature ranges for vegetable trials conducted in 2020 and 2021.

	Treatment	Depth (cm)	60-65ºC	65-70ºC	>70ºC
			·············Time (minutes)················		
Lettuce Trial: #1 2020	Steam alone	10	69 a	43 a	88 a
	Steam + H_2O_2	10	68 a	42 a	76 a
	Control	10	0 b	0 b	0 b
Lettuce Trial: #2 2020	Steam alone	10	40 a	28 a	67 a
	Steam + H_2O_2	10	46 a	31 a	80 a
	Control	10	0 b	0 b	0 b
Spinach Trial: #3 2020	Steam alone	10	109 a	73 a	176 a
	Control	10	0 b	0 b	0 b
Lettuce Trial: #4 2021	Steam alone	10	54 a	35 a	98 a
	Control	10	0 b	0 b	0 b
Carrot Trial: #5 2021	Steam alone	10	48 a	38 a	105 a
	Control	10	0 b	0 b	0 b

Weed densities were measured by number in thousands/acre of weeds. In trial 1, steam and steam + peroxide resulted in 85% and 86% weed control relative to the nontreated control (Table 3). In trial 2, steam and steam + peroxide resulted in 68% and 82% weed control, respectively (Table 3). In trial 3, the steam treatment resulted in 82% weed control relative to the nontreated control (Table 3). In trial 4, the steam treatment result in 100% weed control relative to the nontreated control (Table 3). In trial 5, the steam treatment result in 97% weed control relative to the nontreated control (Table 3)

Table 3: Weed densities from two assessments except Exp 5 of steamed versus unsteamed soil.

Treatment	Weed Densities								
	Exp. 1		Exp. 2		Exp. 3		Exp. 4		Exp. 5
	07/13/20	07/27/20	08/06/20	08/24/21	11/06/20	11/13/21	07/26/21	08/09/21	07/26/21
	No. (1,000s/acre)								
Steam only	104 b	95 b	114 b	130 b	190 b	239 b	0.0 b	0.0 b	40 b
Steam + H_2O_2	103 b	72 b	69 b b	58 b	---	---	---	---	---
Control	729 a	957 a	371 a	378 a	2,270 a	2,110 a	537 a	340 a	1,207 a
P-Value	0.0072	0.0074	0.0134	0.0040	0.0017	0.0280	0.0123	0.0044	0.0142

The dominant weed species in trials 1 and 2 were Hairy nightshade *(Solanum physalifolium*), shepherd's-purse *(Capsella bursa-pastoris*), Little mallow *(Malva parviflora*), and Burning nettle *(Urtica urens)* (Table 4,5). In trial 3, all weeds that were previously mentioned were the most dominant with the addition of Burning nettle and Annual bluegrass *(Poa annua*) (Table 6). In trial 4, it was Hairy nightshade, Goosefoot *(Chenopodium album),* and Shepherd's-purse (Table 7). In trial 5, Hairy nightshade, Purslane *(Portulaca oleracea),* and Burning nettle (Table 8).

Table 4: Reduction in weed densities compared with the untreated control in steamed plots - trial 1.

Treatments	Hairy Nightshade	Mallow	Shepherd's Purse
	Reduction %		
Steam only	91 b	96 c	80 c
Steam + H_2O_2	93 b	91 b	91 b
Non-treated	0 a	0 a	0 a
P-Value	0.0129	0.1053	0.0002

Table 5: Reduction in weed densities compared with the untreated control in steamed plots - trial 2.

Treatments	Hairy nightshade	Mallow	Shepherd's purse	Burning nettle
	Reduction %			
Steam only	64 c	84 c	94 b	84 c
Steam + H_2O_2	84 b	62 b	94 b	100 b
Non-treated	0 a	0 a	0 a	0 a
P-Value	0.2077	0.6210	0.0219	0.0011

Table 6: Reduction in weed densities compared with the untreated control in steamed plots - trial 3.

Treatments	Hairy nightshade	Annual blue grass	Shepherd's purse	Burning nettle
	Reduction %			
Steam only	93 b	96 b	81 b	89 b
Non-treated	0 a	0 a	0 a	0 a
P-Value	0.0372	0.0035	0.0103	0.0282

Table 7: Reduction in weed densities compared with the untreated control in steamed plots - trial 4.

Treatments	Hairy nightshade	Goosefoot	Shepherd's purse
	Reduction %		
Steam only	100 b	100 b	100 b
Non-treated	0 a	0 a	0 a
P-Value	0.0184	0.0471	0.00047

Table 8: Reduction in weed densities compared with the untreated control in steamed plots - trial 5.

Treatments	Hairy nightshade	Purslane	Nettle
	Reduction %		
Steam only	97 b	97 b	97 b
Non-treated	0 a	0 a	0 a
P-Value	0.1683	0.0124	0.0054

Steam reduced hand weeding time from 23-91% compared with the untreated control in all trials (Table 9). Steam + peroxide reduced hand-weeding time by 36-40% compared with the control in all trials (Table 9).

Table 9: Time of hand weeding in five vegetable trials.

Treatment	Hand-weeding time				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
	Hrs/acre				
Steam only	66	50 b	9.2 b	9.8 b	25.6 b
Steam + H_2O_2	55	46 b	---	---	---
Control	86	77 a	49.5 a	117.9 a	130.6 a
P-Value	0.1223	0.0013	0.0001	0.0080	0.0025

The abundance of Pythium colonies in trial 1 was reduced by 50% and 60% in the steam, and steam + peroxide treatments, respectively, compared with the nontreated control (Table 10). In trial 2, the abundance of Pythium colonies from the steam treatment was reduced by 89% and 98% in the steam + peroxide treatment compared to the nontreated control, respectively (Table 10). In trial 3, the abundance of Pythium colonies for steam were reduced by 93% compared with the nontreated control, respectively (Table 11). In trial 4, the abundance of Pythium colonies for steam was reduced by 99% compared with the nontreated control (Table 12). In trial 5, the abundance of Pythium colonies for steam was reduced by 95% compared with the control (Table 12).

Table 10. Abundance of *Pythium* spp. colonies in the seedline before and after steam application for lettuce: trials 1 and 2.

Treatment	Trial 1			Trial 2		
	Pre-treatment	Post-treatment	Reduction %	Pre-treatment	Post-treatment	Reduction %
	····Propagules (n g⁻¹)····			····Propagules (n g⁻¹)····		
Steam only	23.1	11.6 b	50.0	34.1	3.7 b	89.0
Steam+ H_2O_2	24.1	9.7 b	59.7	40.3	0.5 b	98.6
Control	25.1	24.0 a	4.5	38.7	32.1 a	17.2
P-Value	0.6700	0.000243		0.0583	0.000246	

Table 11. Abundance of *Pythium* spp. colonies in the seedline before and after steam application: spinach trial 3.

Treatment	Trial 3		
	Pre-treatment	Post-treatment	Reduction %
	····Propagules (n g⁻¹)····		
Steam only	10.5	0.7 b	93.0
Control	12.1	10.4 a	13.6
P-Value	0.4498	0.001	

Table 12. Abundance of *Pythium* spp. colonies in the seedline before and after steam application: lettuce trial 4 and carrot trial 5.

Treatment	Trial 4			Trial 5		
	Pre-treatment	Post-treatment	Reduction %	Pre-treatment	Post-treatment	Reduction %
	····Propagules (n g⁻¹)····			····Propagules (n g⁻¹)····		
Steam only	24.6	0.02 b	99.9	22.2	0.9 b	95.6
Control	27.4	25.7 a	4.5	19.1	18.6 a	2.5
P-Value	0.0320	0.000124		0.7509	0.00060	

Additionally, the abundance of sclerotia after application in trial 1 for the steam treatment was reduced 77% and 65% in the steam + peroxide treatment compared with the nontreated control (Table 13). Similarly, in trial 2, the abundance of sclerotia after steam treatment was reduced by 85% for the steam and 77% in steam + peroxide treatment compared with the nontreated control (Table 13). In trial 3, the abundance of sclerotia for the steam treatment was reduced by 94% compared with the nontreated control (Table 14). In trial 4, the abundance of sclerotia after steaming was reduced by 72% compared with the nontreated control, respectively (Table 15). In trial 5, the abundance of sclerotia after steaming was reduced by 69% compared to the nontreated control (Table 16).

Table 13. Abundance of Sclerotia in the seedline before and after steam application for lettuce: trials 1 and 2.

Treatment	Trial 1			Trial 2		
	Pre-treatment	Post-treatment	Reduction %	Pre-treatment	Post-treatment	Reduction %
	···Propagules (n g^{-1})···			···Propagules (n g^{-1})···		
Steam only	5.6	1.2 b	77.2	5.8	0.8 b	85.1
Steam + H_2O_2	4.0	1.3 b	65.7	4.5	1 b	77.7
Control	4.5	4.3 a	2.8	6.8	7.3 a	-7.2
P-Value	0.4842	0.2539		0.652	0.1379	

Table 14. Abundance of Sclerotia in the seedline before and after steam application: spinach trial 3.

Treatment	Trial 3		
	Pre-treatment	Post-treatment	Reduction %
	Propagules (n g^{-1})····		
Steam only	4.7	0.2 a	94.7
Control	4.9	7.5 b	-52.7
P-Value	0.6911	0.0002	

Table 15. Abundance of Sclerotia in the seedline before and after steam application: lettuce trial 4.

Treatment	Trial 4		
	Pre-treatment	Post-treatment	Reduction %
	Propagules (n g^{-1})····		
Steam only	3.1	0.8 a	72.1
Control	2.6	2.3 b	9.5
P-Value	0.4517	0.4610	

Table 16. Abundance of Sclerotia in the seedline before and after steam application for carrot: trial 5.

Treatment	Trial 5		
	Pre-treatment	Post-treatment	Reduction %
	Propagules (n g^{-1})····		
Steam only	1.6	0.5	69.1
Control	2.3	1.8	21.0
P-Value	0.5403	0.0631	

Healthy crop counts were conducted for all trials (Table 17). There were no difference in the abundance of diseased plants except for trials 2 and 4 (Table 18). All trials were not pre inoculated and were assessed based off naturally occurring pathogen populations. Trial 4 had the highest abundance of *Pythium* spp. colonies with greater control and a higher yield compared to the other lettuce trials (Table 18).

Table 17. Crop stand count (healthy).

Treatment	Crop Stand (Healthy)				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
	No. (1,000s/acre)				
Steam only	36.8	44.8	419.0	70.8	133.0
Steam +H_2O_2	34.4	46.5	---	---	---
Control	40.4	41.3	416.2	79.5	103.5
P-Value	0.2484	0.7123	0.9418	0.5626	0.1793

Table 18. Number of plants infected with lettuce drop at harvest.

Treatment	Crop Stand (Diseased) Exp. 1	Exp. 2	Exp. 4
	No. (1,000s/acre)		
Steam only	0.8	2.0 b	4.8 a
Steam +H_2O_2	2.3	2.5 b	---
Control	2.0	6.0 a	15.8 b
P-Value	0.1611	0.0013	0.0009

There were treatment effects on marketable yields in trial 4 and there was no treatment effects in the other trials, which is probably due to low disease pressure in the other fields (Table 19).

Table 19: Marketable yield (fresh weight) from 5 vegetable trials.

Treatment	Marketable Yield Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
	Tons/acre				
Steam only	33.1	23.9	13.3	42.3 a	26.6
Steam + H_2O_2	29.7	24.7	---	---	---
Control	25.8	21.4	13.0	30.4 b	23.6
P-Value	0.0131	0.0916	0.8171	0.1624	0.0955

The diameters of lettuce heads in the steamed soil were 15 % larger in trial 1 and 10% larger in trial 2 (Table 20). The lettuce plants grown in the steam + peroxide treated soil were 12% and 20% larger in trials 1 and 2, respectively (Table 20). In trial 4, there was a 10% increase in carrot diameters in steam treated plots compared with the control (Table 20).

Table 20: Lettuce plant diameters and carrot root diameters at harvest.

Treatment	Plant diameters			
	Exp. 1	Exp. 2	Exp. 4	Exp. 5
	Inches/crop			mm/carrot
Steam only	34 a	26 b	32.3 a	28.7 a
Steam + H_2O_2	33 a	29 a	---	---
Control	29 b	23.3 c	24.7 b	25.9 b
P-Value	0.0131	0.0436	0.0116	0.0456

Economic analysis

Operating and Steam applicator cost

This is an economic analysis of the operational costs of a prototype steam applicator build by the University of Arizona and tested in Salinas, CA. The Clayton Sigma Fire 30 model steam generator was purchased from Clayton Industries for $80,051 (Table 21). The custom bed shaper sled was built in Yuma, AZ at Keithly-Williams Fabrication for $25,000 (Table 21). The machine specifications and design costs were obtained from the Clayton website and outside sources (Table 21-22). The total cost of field operation per acre is $971 with an annual machine cost per acre of $127.06 (Table 22). Inputs used in this analysis were:

Table 21. Steam applicator component costs

Chassis frame	$25,000
Generator cost	$80,051
Manufacture Price	**$105,051**
Manufacture margin	3%
Total capital recovery cost	0.229%
Interest rate	0.0475
Equipment life	5 years
Price to operator	**$136,500**

Table 22. Operating and capital costs for steam applicator.

Hours per acre	9.07
Full-time: Machine operator wage/benefits ($/hr)	$24.70
Part-time: Field worker wage/benefits ($/hr)	$18.70
Labor cost ($/acre)	**$393.64**
Propane (gallons/acre)	283.14
Propane price ($/gallon)	$1.59
Fuel cost ($/acre)	**$450.19**
Water usage (gallons/hr)	111
Water cost ($/gallon)	**0.05**
Soft water cost ($/acre)	**$50.33**
Total cost of field operation ($/acre)	**$971**
Annual capital recovery cost	$31,310.49
Annual repair as percentage of initial purchase	0.02%
Annual repair cost	$2,730.00
Total annual steam applicator cost	**$34,040.49**
Hrs. per treatment day	9
Treatment days per year	278
Treatment acres	268
Annual machine cost per acre ($/acre)	**$127.06**

Revenue for Romaine Lettuce

The daily romaine lettuce prices were obtained by averaging daily price calculated as the daily low and high prices using the Agriculture Marketing Service website, 2020 Salinas-Watsonville District (USDA 2020) (Table 23-25). Spalding et al., (2021) utilized a harvest cost of $0.12/lbs. for romaine head of lettuce (Table 24). The pounds per box were obtained by Graham Hunting from the Salinas Agricultural Commissioner's Office (Table 24).

Table 23. 2020 daily price of organic romaine lettuce

Average of mostly high organic ($/box)	$31.59
Average of mostly low organic ($/box)	$29.04
Price for organic romaine ($/box)	**$30.32**
Average of mostly high conventional ($/box)	$28.07
Average of mostly low conventional ($/box)	$26.33
Price for conventional romaine ($/box)	**$27.20**

Table 24. Organic and conventional romaine prices

Harvest cost ($/lb.)	$0.12
Organic romaine heads price ($/lb.)	$1.21
Conventional romaine heads price ($/lb.)	$1.09
Daily price of organic ($/box)	$30.32
Weight of box (lbs./box)	25
Organic head price ($/lbs)	**$1.21**
Daily price of conventional ($/box)	$27.20
Weight of box (lbs./box)	25
Conventional head price ($/lbs.)	**$1.09**

The conventional and organic gross revenue for the lettuce trials were based on steam and the control trial yields, and head prices to obtain head price per lbs. (Table 25). The gross revenue by acre for steam and the control was calculated by obtaining the yields and the area of the plots.

Table 25. Conventional and organic gross revenue for trials 1, 2 & 4.

Lettuce Trial Gross Revenues			
	Trial 1	Trial 2	Trial 4
Steam Yield (tons/acre)	33.1	23.9	42.3
Control yield (tons/acre)	25.8	21.4	30.4
Conventional head price ($/lbs)	$1.09	$1.09	$1.09
Gross conventional revenue steam ($/box)	**$36.02**	**$26.05**	**$46.10**
Gross conventional revenue control ($/box)	**$28.07**	**$23.33**	**$33.13**
Organic head price ($/lbs)	$1.21	$1.21	$1.21
Gross organic revenue steam ($/box)	**$40.14**	**$28.92**	**$51.18**
Gross organic revenue control ($/box)	**$31.29**	**$25.89**	**$36.78**
Gross conventional revenue steam ($/acre)	**$1,736**	**$1,255**	**$5,066**
Gross conventional revenue control ($/acre)	**$1,352**	**$1,124**	**$3,640**
Gross organic revenue steam ($/acre)	**$1,934**	**$1,393**	**$5,624**
Gross organic revenue control ($/acre)	**$1,508**	**$1,247**	**$4,042**

Discussion

Management of weeds in high-value vegetable production systems is challenged by a lack of herbicides and a shortage of labor for hand weeding. Farmers are put in a difficult spot in trying to implement appropriate management plans to control pests and avoid chemical resistance while growing quality produce. Thermal methods to eliminate or reduce pathogens and weed seed in the soil may be a way to supplement the pest control needs of vegetable growers. Traditional steam pasteurization techniques used stationary methods of soil steaming commonly used in greenhouse production and is not suitable for in-field applications (Melander et al., 2005). Melander et al. (2005) and Pinel et al. (1999) suggested the need for a mobile steamer band application method which may provide an effective non-chemical alternative to soil fumigants. Steam pasteurization is especially attractive for organic farmers who have few tools to tackle pest management or conventional farmers who need to treat buffer zones in their fields when fumigants may not be applied. I learned that the ability to adjust the speed of application to control the soil temperature was an advantage in that it was possible to avoid over application of steam. We evaluated three steam applicators, two of which were commercial models that worked really well in field production sites. However, there is a need for improvements to consider in terms of design and speed. Steam was injected into the soil with a target temperature of 70^{o}C, which was accomplished and maintained for 20 min dwell time in all trials. Soil temperature results gathered after steam application in the field were similar to other mobile steamer applicator studies (Pinel et al., 1999, Melander et al., 2005, Carlesi et al., 2021, Kim et al., 2021).

The premise of this research was to evaluate the pest control efficiency of steam applied in a band prior to planting. We found that weeds, pathogens, and hand weeding times were reduced in steam-treated plots, and yields improved in some cases. In trial 3, for 176 min, steam temperatures were above 70^{o}C were obtained with the Steamy applicator, which used a rototiller as it was incorporating steam on flat ground. Agitating the soil as the steam was incorporated allowed for better steam penetration targeting soil aggregates compared with trials 4 and 5 done by the Yuma Steamer. The Yuma steamer kept a steam temperature above 70^{o}C for 98-105 minutes. The temperature duration time above 70^{o}C for the Yuma steamer was not as long as the temperature duration in the Steamy applicator trial. The Yuma steamer has a bed shaper attached to it to ensure the bed tops stay firm after application and is faster than the Steamy.

The results from the weed analysis indicate that steam disinfestation does an excellent job controlling weeds, especially on hairy nightshade, goosefoot, sheperd's-purse, burning nettle, and common purslane. Another objective in this study was to evaluate steam + hydrogen peroxide applied as a band to determine whether this product improves the pest control efficacy of steam by raising the temperature. Hydrogen peroxide did not have a significant effect on weed and pathogen control, hand weeding time, and yields compared with the steam treatments. Because the trials used soils naturally infested with *Pythium* spp. and *S. minor*, we had varying levels of disease in the field trials. Steam + hydrogen peroxide did not significantly reduce the amount of *Pythium* spp. colonies or *S. minor* sclerotia compared with steam alone. In trial 2, upon steam application, temperatures stayed above 70°C for a shorter amount of time compared to the other trials (67-88 mins). The steam treatment had a significant effect on reducing *S. minor* sclerotia by 94% when compared with the control using the Steamy in trial 3, similar to findings in other studies (Triolo et al., 2004, Pinel et al., 2000). The steam treatment reduced *Pythium* spp. colonies by 99% when compared with the control using the Yuma steamer in trial 4, similar to another study that was done (Pinel et al., 2000). Out of all the trials, trial 4 had the most diseased lettuce plants and the best reduction of *Pythium* spp. colonies. The lettuce plant size for the steam-treated lettuce was significantly larger with an increase in yield when comparing with the control in trial 4 and 2, suggesting pathogen suppression.

Gross revenues for the lettuce trials in this research showed the potential steam has to increase lettuce yields. A steam study done in strawberry production by Michuda et al., (2021) suggested a maximum soil temperature of 62-63°C should be a standard for growers at a duration of 41-44 mins to maximize net returns and increase fruit yield. In our lettuce steam study we surpassed that reaching temperatures above 70°C which increased yield and gross revenue per acre. Better disease control likely resulted in greater lettuce growth with a gross organic revenue of $5,624 an acre for the steam treated lettuce vs. 4,042 an acre for the non-treated control lettuce. The difference was $1,582 an acre. For the gross conventional revenue, it was 5,066 an acre for the steam treated lettuce vs. $3,640 an acre for the non-treated control lettuce. The difference was $1,426. The cost of field application per acre is $971, which suggests steam treatment maybe economically feasible to use commercially in-field given the great gross revenues per acre, but we believe that there is room for improvement in this cost. Machine operator and worker wage will increase the operating costs of this field applicator as the cost of minimum wage increases in the future, so more research needs to be done to drive the costs of the applicator down.

Research and development should focus on the implementation of a rototiller to agitate the soil to target soil aggregates for better steam penetration. Improvements might include making the machine lighter so that there is less compaction. Ideally, machine development and construction should be done in the United States to reduce the overall price of the applicator. It is important to increase the speed of application, but it needs to be done in a way that the machine still heats the soil and makes adequate dwell time. Currently, it takes 9.07 hours to steam an acre, so if the time of application can be reduced, then the amount of fuel costs can be reduced as well. It will be of great benefit to work with a known industry leader like, TriCal Inc. because they specialize in developing new effective technologies and build products to control soil pests in California. Steam applicator development can be maximized with the help of contractors who have the capabilities of building a steam applicator who can lease out to farmers. Steam is also an option for organic farmers to make an applicator in house that can be of great benefit given the need for non-chemical ways of controlling soil pests.

Nevertheless, my results indicate that with a greater reduction of pathogen inoculum and weed seeds in the soil using steam, this will allow more opportunity for the crop to thrive with less pest competition. Even though the hydrogen peroxide treatment was evaluated only in two of five trials, there was no significant advantage when compared to the steam treatment alone. Hydrogen peroxide still has potential to create an exothermic effect in the soil steaming process. As a recommendation for future studies if hydrogen peroxide is more thoroughly incorporated into the soil and the trial is pre-inoculated with soil pathogens, there may be a yield benefit. This work further shows the true potential of band steaming for weed and pathogen control in the field (Carlesi et al., 2021).

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