OZONE GAS AS A SOIL FUMIGANT

CONSULTANT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Electric Power Research Institute

October 1999
500-02-051F

Prepared By:
Electric Power Research Institute (EPRI)
3412 Hillview Avenue
Palo Alto, California 94304
Contract No. 100-98-001

Prepared For:
California Energy Commission

Gary Klein
Contract Manager

Terry Surles
Program Manager
Public Interest Energy Research Program

Marwan Masri
Deputy Director
Technology Systems Division

Robert L. Therkelsen
Executive Director

Ozone Gas as a Soil Fumigant

1998 ResearchProgram

TR-113751

Final Report, October 1999

Cosponsors:
Public Interest Energy Research Program (PIER)
California Energy Commission
1516 Ninth Street
Sacramento, California 95814

EPRI
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
M. Jones

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI Agricultural Technology Alliance

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax). Copies of this report may also be downloaded from the California Energy Commission's website: http://www.energy.ca.gov/research

CITATIONS

This report was prepared by the EPRI Agricultural Technology Alliance by

SoilZone, Inc.
Davis, California

Principal Investigator
A. Pryor

This report was prepared for

EPRI
3412 Hillview Avenue
Palo Alto, California 94304

and

Public Interest Energy Research Program (PIER)
California Energy Commission
1516 Ninth Street
Sacramento, CA 95814

This report describes research jointly sponsored by EPRI and the California Energy Commission.

The report is a corporate document that should be cited in the literature in the following manner:

Ozone Gas as a Soil Fumigant: 1998 Research Program, EPRI, Palo Alto, CA, California Energy Commission, Sacramento, CA: 1999. TR-113751.

REPORT SUMMARY

Background

To meet the challenge to develop environmentally friendly alternatives to the scheduled phaseout of methyl bromide (to be banned starting in 2001) for soil fumigation, SoilZone, Inc. in 1998, conducted ten field trials utilizing injection of on-site generated ozone gas into the soil. In 1997, SoilZone, Inc, began field trials in California as an attempt to develop this new technology for agricultural and horticultural markets.

Objectives

Initial success in carrot and tomato trials prompted SoilZone, Inc. to request and receive matching assistance contracts from EPRI and Edison Technology Solutions to more widely test this technology to:

- Control soilborne pathogens
- Increase yields in a range of crops in different geographical locations.

This report documents the results of these field trials.

Approach

Ozone injection trials using buried drip tubes and injection probes were conducted in plots utilizing randomized complete block techniques. Upon harvest crop yields were measured, final soil samples collected and statistical analyses completed.

Results

The results of these field trials generally demonstrate the broad effectiveness of ozone treatment in soils to increase plant yield and reduce the detrimental effects of soil pathogens on a variety of crops and soils under a range of climatic conditions.

When the ozone preplant application was compared to untreated controls, improvements in crop yield and plant vigor were seen in all except the peach trials. The results indicate that soil treatment with ozone results in decreased soil pathogen pressures (due to its biocidal effects) and increased nutrient availability (due to oxidation of organic compounds). Applied as a preplant treatment, these two benefits promote increased plant growth and yield without detrimental environmental effects. Much additional work is necessary to be able to accurately predict the specific growth response achieved by ozonation in different crops, soils and climatic conditions.

EPRI Perspective

EPRI has supported and promoted the development of ozone technologies for its utility customers. In recent years customers, specializing in water, wastewater, food and agriculture have seen the use of ozone become vitally important.

The popularity of ozone usage is based on several factors:

- It is manufactured on site; thus eliminating transportation, storage or accidental discharge of hazardous or toxic chemicals
- It has a very short half-life; thus reducing buildup of toxic compounds
- It has minimum human toxicity
- It does not leave environmentally persistent chemicals in the soil

These benefits are consistent with the intent that EPRI supported research should be directed to electrotechnologies which provide economic benefits to energy consumers while providing environmentally safe alternative technologies.

Keywords
Ozone
Fumigants
Drip Irrigation
Tomatoes
Carrots
Strawberries
Sugar Beets
Broccoli
Prunes
Sweet Potatoes
Peaches

ACKNOWLEDGMENTS

This research report represents the culmination of many thousands of hours of hard work and effort by researchers, technicians, laborers, growers, and managers. Grateful acknowledgement is offered to all of those dozens of people who willingly contributed their time and are simply far too numerous to mention individually. Appreciation is also expressed to Lory Larson of Edison Technology Solutions, Myron Jones of the Electric Power Research Institute, Chuck Sopher, Gary Obenauf, and Greg Schwaller of the EPRI Agricultural Technology Alliance, Ricardo Amon of the California Energy Commission, and Roger Sung for their invaluable assistance in arranging project financial support and report management.

CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Background

Ten field trials were performed during 1998 in California testing the efficacy of preplant injection of on-site generated ozone gas into the soil to control soil-borne pathogens and increase yields in commercially important crops in a range of different geographical areas. Ozone was injected at rates varying by crop of from 50 to 400 lbs per acre (56 to 448 kg/ha) through buried drip tubing for row crops or through shanks inserted into the location of tree replants.

The row crops were strawberries, tomatoes, carrots, sweet potatoes, and broccoli. The tree replants were peaches and prunes. The results of these field trials generally demonstrate the effectiveness of ozone treatment of soil in increasing plant yield and reducing the detrimental effects of soil pathogens. In every trial except the peach trial, numerical improvements in crop yield or plant vigor resulted from the ozone preplant application compared to untreated controls. Results were variable when comparing ozone and conventional fumigants

Tests were also conducted to test the efficacy of coinjection of carbon dioxide with the ozone and injections of smaller amounts of ozone during the growing season. The effects of mixing carbon dioxide with the ozone gas when injected as pre-plant treatment were not conclusive.

All data are presented and where available, statistical analyses are provided. All statistical analyses were conducted at the 90% level of significance. The results of these studies provide sufficient evidence that ozone enhances crop production through reduction in microbial activity and/or enhanced oxygen levels in the root zone.

Much additional work will be necessary to quantify the specific growth responses achieved by ozonation in different crops. Controlled statistical studies with larger numbers of replications will be needed to determine the mechanisms by which ozone treatment enhances yields.

1 INTRODUCTION AND BACKGROUND

As a result of the pressing need to develop environmentally benign alternatives to methyl bromide for soil fumigation which is scheduled for phase out, SoilZone commenced field trials in 1997 attempting to develop a new technology for the agricultural and horticultural marketplaces. This technology utilizes injection of on-site generated ozone gas into the soil. Based on the initial success of these independently evaluated trials in carrots and tomatoes, SoilZone believed its ozonation technology could potentially provide an alternative to methyl bromide for soil treatment. SoilZone subsequently requested and received matching research assistance contracts from the EPRI Agricultural Technology Alliance and the California Energy Commission through Edison Technology Solutions to perform ten field trials in California. These trials were designed to more broadly test the efficacy of this technology in controlling soil-borne pathogens and increasing yields in commercially important crops in a range of crops in different geographical areas. This document reports the results from these field trials.

Environmental and Regulatory Status of Methyl Bromide and Alternative Fumigants

Soil fumigation is widely practiced in the United States to destroy a variety of soil-borne microorganisms prior to planting. Many crops are highly susceptible to attack by such bacteria, fungi, and nematodes which collectively cause billions of dollars annually in crop losses. The most popular fumigant, methyl bromide, is extremely effective as a soil-fumigating agent. It is also highly toxic. It is the most functional and widely used fumigating agent with the broadest biocidal spectrum currently available. As a result, its use has grown exponentially over the past 20 years, now reaching 53,000,000 lb (2.4×10^7 kg) per year in the United States. Methyl bromide is being phased out rapidly, however, due to claims of its deleterious long-term effects on the ozone layer and to human health and safety concerns.

For instance, the Montreal Protocol to which the United States is a signatory country mandates a gradual phasing out of methyl bromide beginning in 1999 and culminating in complete elimination by the year 2005.

There currently is no panacea on the horizon that can broadly displace the use of methyl bromide when it is ultimately banned. Most alternative chemical treatments have substantial human health and safety risks or environmental persistence or toxicity problems associated with their use. For instance, Telone (a mixture of 1,3 Dichloropropene and Chloropicrin) and Vapam (containing metam sodium) are both on the Proposition 65 list in California. Telone’s use throughout California is limited because of its air pollution potential. It is expected that similar restrictions will be put on Vapam in the near future.

Other fumigants either have strong odors associated with their use which preclude their application near residential areas or have severe phytotoxicity problems if degradation in soil does not occur in the prescribed time period before crop planting. Other alternatives have yet to have efficacy established on a broad basis and have inherent obstacles to overcome. These include steam sterilization (large water requirements), plastic mulch solarization (time duration required and disposal of contaminated used plastic), organic fortification such as manure or cole crop residues (limited large-scale availability and limited efficacy), and cultural practices such as cropping, cover crops, field sanitization (limited efficacy). In contrast, ozonation is easily to apply with limited releases into the atmosphere. Any such releases are minimal compared to the total ozone levels in an ambient envelope and have a half-life of 12 hours or less in the atmosphere with simple diatomic oxygen as its decomposition product. The technology can be easily incorporated into existing cultural practices, and requires no onsite transportation, storage, handling or discharge of unnecessary toxic chemicals.

Summary of Potential Environmental and Human Health and Safety Benefits of Ozonation

The lack of broadly accepted alternatives to methyl bromide has created an urgent need for functional, environmentally benign, and cost-effective substitutes. In marked contrast to currently accepted soil treatments, ozone offers substantial environmental and safety and health benefits:

Onsite Manufacture - No Transportation, Storage, or Discharge of Hazardous or Toxic Chemicals

Because ozone is manufactured on site at low pressures, it cannot be stored and is immediately consumed in the soil treatment process. A widespread sudden release of ozone into the atmosphere that would be harmful to humans cannot occur as it could with compressed methyl bromide or other persistent, toxic gases or chemicals. Further, because ozone-manufacturing equipment, not chemicals, are transported, there is no danger of spills or releases in the event of equipment transportation accident. In the event of a major accident on site, a properly controlled ozone generator will simply shut down with no further production or release of the gas. For instance, an earthquake of the magnitude that might topple drums of chemicals or cylinders of compressed agricultural gases, or a large industrial fire that might ignite such chemicals or gases, would almost certainly result in interruption of some utilities to the ozone generator (i.e. electricity, air, or cooling water). This would immediately terminate any further ozone production and release. Further, because ozone itself is consumed in the treatment process, there are no discharges.

No Environmentally Persistent Chemicals Left in Soil

Ozone has a very short half-life of minutes or less in soil and decomposes in simple diatomic oxygen. Use of ozone in soil treatment will not result in the buildup of any environmentally persistent or toxic compounds.

No Reentry, Permitting, or Use Restrictions

Ozone is regulated by the EPA as a "biocidal device" and is thus exempt from further registration requirements by the EPA for state regulatory agencies. The California Department of Pesticide Regulation has confirmed this interpretation in writing. In addition to the associated lack of permitting requirements, the short half-life of ozone allows virtual immediate reentry after application without any risk of adverse exposure to workers.

Minimum Human Acute and Chronic Toxicity - No Human Carcinogenicity or Teratogenicity

Except is extremely rare cases of extended, severe overexposure to high concentration of ozone (several hours at greater than 2-3 ppm), the physical symptoms of ozone exposure are transitory in nature. Indeed, ozone has been used commercially in water treatment for over 100 years in tens of thousands of installations without a single recorded fatality. The symptoms at lower concentrations include watery eyes, tightness in the chest, shortness of breath, and irritated throat. Headaches or light-headedness are common. These symptoms generally begin to subside once the exposure is ended. Complete recovery occurs within hours or, in severe cases, days. Additionally, ozone is not considered a carcinogen, teratogen, or mutagen by any regulatory bodies. This is contrasted with the accumulation and buildup of toxic concentrations of many other chemicals in living tissues or soils leading to chronic toxicity.

No Broad Spectrum Environmental Toxicity

Ozone's use as a preplant treatment merely mimics and enhances the same natural oxidative soil processes already occurring in the soil. Further, although ozone is considered an airborne pollutant due to its formation in air from urban and natural air contaminants, proper use of ozone in aqueous applications is actually exempted from regulation by many regional air pollution control districts. For instance, the South Coast Air Quality Management District, the country's largest air pollution control district, covering most of Southern California, has categorically exempted ozone from all permitting requirements for aqueous applications.

Project Approach

SoilZone, Inc. had been investigating the biocidal aspects of ozone gas for several years when injected into different soils under laboratory conditions. Subsequently, field trials were conducted in conjunction with the proposed coinvestigator, Dr. Becky Westerdahl at the University of California, Davis under grant from the EPA. In these trials conducted at the University of California South Coast field station in Irvine, ozone preplant treatment of soil for tomatoes at the rate of 250 lb of ozone per acre (280 kg/ha) resulted in an 75% increase in total tomato fruit weight under certain conditions compared to untreated controls. The increase in fruit weight of the tomatoes grown in ozone treated soil was also 13% greater than the total fruit weight achieved in Telone treated soil. The ozone treatment in carrot plots produced an approximate 60% increase in marketable carrots compared to untreated controls. Based on these trials, it has been demonstrated that ozone has the potential to be a functionally viable, cost-effective, and environmentally benign alternative to methyl bromide use. If the technology is to realize its full potential, substantial additional fieldwork needs to be done to fully evaluate and optimize conditions for maximum benefit at minimum cost.

The objective of this research was to determine and demonstrate the efficacy of soil treatment with ozone in increasing yields in field trial scale applications in a geographically diverse variety of important California crops. Varying application dosages and duration were used in all trials and produce yield and quality from treated plots were compared to those from untreated control plots. In some cases, plots were treated with alternative fumigants. Where applicable, soil pathogen pressures and/or active soil-borne fungi and bacteria populations were determined and correlated with crop yield and treatment.

2
CONCLUSIONS AND RECOMMENDATIONS

Project Conclusions

This research met the project objectives, as follows:

- The research demonstrated the broad effectiveness of ozone treatment of soil in increasing plant yield and reducing the detrimental effects of soil pathogens in a strawberries, carrots, tomatoes, prune orchard replants, broccoli, and sweet potatoes in a variety of soils under a range of climatic conditions. Although numerical increases were noted in 9 of the 10 trials, statistical significance of these differences was not obtained in over half the trials. Combined with the unusual warm and moist weather patterns induced by the El Nino weather phenomena, reproducibility under many different applications and conditions must be established before future widespread use results.
- The research determined the maximum applied dosage and rate of application of ozone for midseason applications without phytotoxicity in the form of lower leaf burn.
- The research determined the effects of mixing carbon dioxide with the ozone gas when injected as pre-plant treatment tended to be positive but these results were not statistically significant.

Potential to Apply/Use Research Results and Future Research Recommendations

This technology has broad potential commercial applications within the California electrical service territory. Vegetable growers, strawberry growers, orchardists, and nursery operators are all agricultural end users that could potentially benefit from this technology and they are distributed along the entire length and breadth of the state.

Prior to commercialization, the following milestones will need to be met in order to convince research advisors and farmers of the technology benefits.

- Demonstrate the reproducibility of the previous year's positive small scale field trial results achieved by preplant ozonation. This should be performed in the same crops in the same location with the same pathogens as in the prior year for a majority of the trials. Demonstrate positive field trial results in additional crops under different conditions.
- Demonstrate economic effectiveness of ozone technology in large-scale commercial field trials.
- Further investigate the use of carbon dioxide in conjunction with ozone.

Public Interest Benefits if Research Results Are Applied/Used

The benefits to agribusiness, consumers, and the environment potentially provided by soil treatment with ozone are consistent with the intent of EPRI that research be directed to sectors that can provide energy efficiency improvements while providing significant benefits for both agricultural users and electrical consumers and preventing significant natural resource degradation. These benefits are further elucidated below:

- **Energy Efficiency** - Elimination of the inefficient total energy consuming components of the manufacture, transportation, storage, application, and waste discharge of methyl bromide can provide overall energy net efficiency benefits to the farming community and the consumer population and society at large.
- **Prevention of Natural Resource Degradation** - The use of site generated ozone as a soil treatment method could materially contributes to the successful phase out of methyl bromide thus preventing further degradation of the ozone layer which is perhaps the most fragile of our natural resources. Further, because ozone does not sterilize soil as is the case with methyl bromide, a more favorable and diverse microbiological soil is maintained contributing to the vitality and sustainability of the soil.
- Elimination of methyl bromide will also eliminate the continued contamination of soil runoff or percolated ground water with bromide ion and other bromine containing byproducts thereby preventing further degradation of natural water resources of critical importance to consumers as a source of drinking water.

If the technology is developed to its full potential, this will result in substantial additional electrical consumption in California due to the electrical requirements for manufacture of ozone (approximately 11 kWh per pound (24 kWh per kg) of ozone). This increased electrical usage will be offset by decreases of energy use associated with methyl bromide fumigation (manufacture, transportation, and application). Although the scale of applicability of ozone as a replacement for all current methyl bromide soil fumigation applications is uncertain, the technology can potentially be developed as a replacement for methyl bromide based on a 1:1 weight ratio. If so, based on current total national annual consumption of methyl bromide for preplant applications of 55,000,000 lbs (2.5×10^7 kg) and at a total power consumption of 11 kWh for each pound (24 kWh per kg) of ozone produced (for both ozonator and compressor power), this would result in annual electrical consumption of 605,000,000 kWh or $54,450,000 worth of power at the retail price of $.09/kWh.

Economics

The economic effectiveness of the ozone treatments is more difficult to ascertain than in the case of conventional agricultural fumigants that are sold and delivered by the pound to the grower. In the case of soil treatment with ozone, the two components of the cost of ozonation are the operating costs to run the ozonation equipment including labor and transportation overhead and the amortization of the capital cost of the ozone producing equipment. The amortization component of the cost representing one pound per day of ozone generating capacity is extremely variable. It primarily depends on whether the equipment is used on a continuous basis or only intermittently. A large-scale ozonation system could be procured for about $750 for 1 lb/day ($340 for 1 kg/day) of capacity. Amortization of $750 over 7 years at 7% would equal a daily "per pound" payment of $0.40 ($0.88/kg). Assuming the system is utilized at 50% of capacity over the course of the year, this would equal a equipment amortization cost of $0.80/lb ($1.76/kg). Operating costs for production of ozone are assumed to equal $1.00/lb ($2.20/kg). (11 kWh /lb (24 kWh/kg) electrical requirements x $0.09/kWh electrical cost). Maintenance, labor and repair, and transportation costs are assumed to equal approximately $0.80/lb ($1.76/kg) for a total production cost of approximately $2.60/lb ($5.73/kg). Thus, a service company could provide on site delivery of ozone for between $3.50 – $4.00/lb ($7.72 - $8.82/kg) with cash margins of approximately 33 percent.

Assuming the ozone delivery injection tubing is also used for irrigation during the growing season can that the delivered price of ozone is $3.50/lb ($7.72/kg), then an applied dosage of 50 pounds of ozone per acre (56 kg/ha) could be secured for a total price of $175/acre ($432/ha). This is very competitive with both Vapam and Telone. A dosage of 250 lbs per acre (280 kg/ha) of ozone would cost $875/acre ($2160/ha). This is competitive with present methyl bromide costs.

3
DISCUSSION

Methodology

Ten field trials were performed under these research contracts. The crops, California location, collaborators, and methods of ozone injection are listed below. In all trials, SoilZone was responsible for experimental design and application of ozone. SoilZone was also responsible for drip tube placement in all trials except those in Irvine with Dr. Becky Westerdahl. Collaborators were responsible for crop planting and cultural practices. Drs. Westerdahl and Duniway were also responsible for crop harvest and grading which SoilZone provided in all other trials with non-academic collaborators.

No.	Crop	Location	Collaborator	Method Of Ozone Injection
1	Tomatoes	Irvine	Dr. Becky Westerdahl, UCD	Buried Drip Tube
2	Tomatoes	Tulare	Edison AgTAC/EPRI-ATA	Buried Drip Tube
3	Carrots	Irvine	Dr. Becky Westerdahl, UCD	Buried Drip Tube
4	Carrots	Tulare	Edison AgTAC/EPRI-ATA	Buried Drip Tube
5	Strawberries	Watsonville	Dr. John Duniway, UCD	Buried Drip Tube
6	Sugar Beets	Irvine	Dr. Becky Westerdahl, UCD	Buried Drip Tube
7	Broccoli	Santa Maria	Rancho Laguna Farms	Injection Probe
8	Prune Replant	Orland	Steve Brown	Buried Drip Tube
9	Sweet Potatoes	Stevenson	Nakashima Farms	Buried Drip Tube
10	Peach Replant	Winton	Mallard Bend Farms	Injection Probe

All ozone injection through drip tubing utilized 1/2” (13 mm) PVC tubing with 12” (305 mm) emitter spacing. Tubing was buried 6” (152 mm) deep in bed centers except for strawberries where double injection tubes were used for each bed and buried 10” (254 mm) from bed edges. Injection tubing so used was left in place throughout the duration of the trial and was used for subsequent midseason applications of ozone in the carrot and tomato trials in Tulare.

In the Irvine tests, the same drip tubing was used both for ozone injection and subsequent irrigation. Ozone for orchard replants was applied through a 1/2" (13 mm) steel injection probe with 3/8" (10 mm) emitter holes drilled between 8 and 18" (203 and 457 mm) depth. A 6-ft. square (0.6 m^2) of plastic mulch was laid down over each injection site and sealed around the injector in the center and around the plastic edges with dirt. All applications utilized ozone produced in air unless otherwise indicated.

Ozone treatments were generally under moistened conditions at about half of field capacity and proceeded planting by 3-7 days. Plots were laid out in randomized blocks. Upon harvest of the crops, yields were segregated and weighed and final soil samples were obtained.

Ozone gas was injected into preirrigated or moistened soil through either buried drip tubing (for row crops) or a single point injection shanks (for orchard replants). The following describes the method of ozone injection and different ozone treatments employed at each trial.

No.	Crop	Ozone Injection Method (1)	Ozone Treatments (lbs O_3/acre or /tree) (2)
1	Tomatoes, Irvine	0.5 gph@12" Emitter Drip Tube	250 lb O_3 w/ & w/o Preirrigation, 250 lb O_3 in O_2, 50 lb O_3, 50 lb O_3 w/ 100 lb CO_2
2	Tomatoes, Tulare	4.0 gph@12" Emitter Drip Tube	50 & 250 lb O_3
3	Carrots, Irvine	0.5 gph@12" Emitter Drip Tube	250 lb O_3 w/ & w/o Preirrigation, 250 lb O_3 in O_2, 50 lb O_3, 50 lb O_3 w/ 100 lb CO_2
4	Carrots, Tulare	4.0 gph@12" Emitter Drip Tube	50 & 250 lb O_3, 50 lb O_3 w/ 2 x 15 lb Midseason
5	Strawberries	4.0 gph@12" Emitter Drip Tube	400 lb O_3, 400 lb O_3 w/ 100 lb Trichoderma w/ 1 x 15 lb Midseason (3)
6	Sugar Beets, Irvine	0.5 gph@12" Emitter Drip Tube	250 lb O_3 w/ & w/o Preirrigation, 250 lb O_3 in O_2, 50 lb O_3, 50 lb O_3 w/ 100 lb CO_2
7	Broccoli	2.0 gph@12" Emitter Drip Tube	50 & 250 lb O_3
8	Prune Replant	Probe/Mulch (4)	1.25 lb O_3/tree hole
9	Sweet Potatoes	2.0 gph@12" Emitter Drip Tube	100 & 400 lb O_3
10	Peach Replant	Probe/Mulch (4)	1.25 lb O_3/tree hole

Note: 0.5 gph = 0.002 m^3/h, 2.0 gph = 0.008 m^3/h, 4.0 gph = 0.02 m^3/h
12" = 305 mm
15 lb/acre = 17 kg/ha, 50 lb/acre = 56 kg/ha, 100 lb/acre = 112 kg/ha,
250 lb/acre = 280 kg/ha, 400 lb/acre = 448 kg/ha
1.25 lb/hole = 0.6 kg/hole

1. All ozone injection through drip tubing utilized 1/2” (13 mm) PVC tubing with 12” (305 mm) emitters spacing (Drip-In, Madera, CA). Tubing was buried 6” (152 mm) in bed center except for strawberries where double injection tubes were used buried 10” (254 mm) from bed edges. Injection tubing so used was left in place throughout the duration of the trial and where so designated was used for subsequent midseason applications of ozone. In the Irvine tests, the same drip tubing was used both for ozone injection and subsequent irrigation.

2. All applications utilized ozone produced in air unless otherwise indicated. All ozone treatments preceded planting by 3-7 days.

3. Trichoderma T-22 granules (Bioworks, Inc.)

4. Ozone was applied through an injection probe with 3/8” (10 mm) emitter holes drilled between 8 and 18” (203 and 457 mm) depth. A 6-ft. square (0.6 m^2) of plastic mulch was added around each injection site and sealed around the injector and plastic edges with dirt.

Plots were laid out in randomized blocks. Following is a summary of the treatment block size, number of replications of each treatment, and other pertinent treatment data. The number of different treatments and minimum number of replications per treatment (from 3 to 10) was chosen given the available field trial space or number of replant sites at each location. Ozone was injected at the maximum rate allowed given the drip tubing emitter size. A number of other treatment options were not tested at different sites because of the available field trial space. These include injection of air, oxygen, or CO_2 without ozone, the most beneficial time following ozone application in which a crop is planted. Minimum soil moisture levels on ozone application of 10% were ensured by preirrigation. Preirrigation has been shown to produce higher yields when treated with ozone compared to non-preirrigated soils in prior tests. Maximum ozone application dosages were selected which can be applied at what are believed to be approximately equivalent costs to the grower compared to methyl bromide or alternative fumigants.

No.	Crop	No. of Reps & Plot Size per Treatment	Soil (%) Moisture at Application	O_3 Conc. (%w/w)
1	Tomatoes, Irvine	Six – 20 ft x 34 in. (6 m x 0.9 m)	12 – 17 %	2.7 – 6.0
2	Tomatoes, Tulare	Six – 20 ft x 34 in. (6 m x 0.9 m)	10 – 14 %	2.7 – 6.0
3	Carrots, Irvine	Six – 20 ft x 34 in. (6 m x 0.9 m)	10 – 14 %	2.7 – 6.0
4	Carrots, Tulare	Six – 20 ft x 40 in. (6 m x 1 m)	17 – 18 %	1.6 – 1.8
5	Strawberries	Three – 20 ft x 52 in .(6 m x 1.3 m)	8 – 11 %	1.8 – 2.0
6	Sugar Beets	Six – 20 ft x 34 in. (6 m x 0.9 m)	12 – 17 %	2.7 – 6.0
7	Broccoli	Six – 30 ft x 38 in. (9 m x 1 m)	14 – 16 %	1.8 – 2.0
8	Prune Replant	Ten Trees – 20’ (6 m) OC –	13 – 18 %	1.5 – 1.6
9	Sweet Potatoes	Six – 20 ft x 40 in. (6 m x 1 m)	11.2 %	2.5 – 2.8
10	Peach Replant	Ten Trees – 20’ (6 m) OC –	8 – 11 %	1.8 – 2.0

Field Test Results

Following is a descriptive summary of each trial and a discussion of the produce yields and/or growth response from the ten field trials completed during 1998. Results were analyzed using Analysis of Variance (ANOVA)[1] at the 90% level. Statistically different treatments are identified by a different lower case letter above each bar in the histograms that follow, for each set of results. For example, a bar with the “a” alone or in combination with other letters above it, differs significantly from those bars which do not have an “a” in any combination above it.

Tomatoes

- **1998 South Coast Tomato Field Trials** – These trials were performed in a field heavily infested with root knot nematodes at the University of California South Coast Field Station in Irvine, California. The research was conducted in conjunction with Dr. Becky Westerdahl of the University of California at Davis Department of Nematology. Ozone was injected in early July with and without pre- and post-irrigation at the rate of 50 or 250 lb per acre (56 or 280 kg/ha) (with and without oxygen or CO_2) through underground drip tubing buried 4-6 inches (102-152 mm) deep in the center of 32” (813 mm) furrows. Tomato seedlings were planted 3 weeks later and the total yield and number of root galls were compiled at the end of the September harvest and compared to untreated control and other fumigant treated plots. In these trials, *ozone treatment at 250 lb per acre (280 kg/ha) following pre-irrigation increased total fruit production by approximately 44% compared to untreated controls. This was equal to the metam sodium treated plots and 17% greater than yields in Telone treated plots. Ozone treatment at 50 lb per acre (56 kg/ha) with 100 lb per acre (112 kg/ha) carbon dioxide increased yield by 30% compared to untreated controls (see Figure 3-1).*

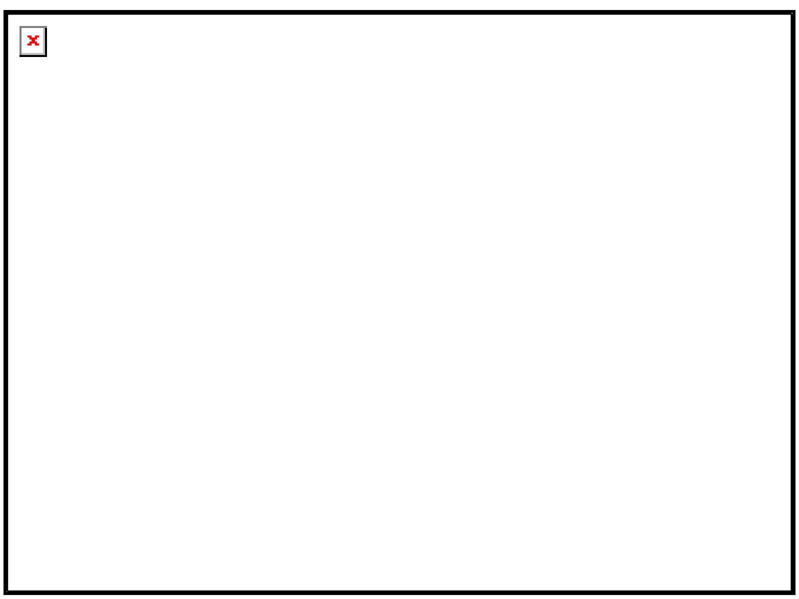

Figure 3-1
1998 Tomato Yield (Lbs/Plot)

[1] Brykit, Donald. 1972. Elements of Statistics, Van Nostand Reinhold Co., New York. p.215.

The extent of nematode root galling was not lower in the ozone treated plots than in the Telone treated control plots despite the improved yield in the ozone treated plots (see Figure 3-2). This indicates that biostimulation (probably due to increased nutrient availability) in addition to the biocidal aspects of ozone treatment are also important in plant yield.

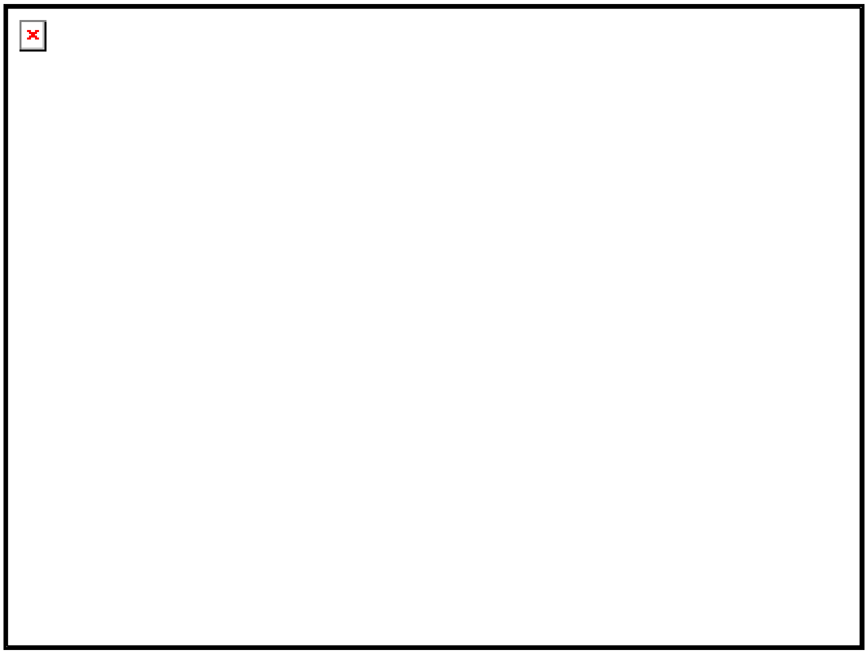

Figure 3-2
1998 Tomato – Root Gall Rating

- **1998 AgTAC Tomato Field Trials** – These field experiments were performed during the spring and summer of 1998 at the Southern California Edison AgTAC Research Center in Tulare, California in conjunction with the Electric Power Research Institute. Ozone was injected at the rate of 250 lb or 50 lb per acre (280 or 56 kg/ha) through underground drip lines buried about 6 inches (152 mm) in the center of 40” (1 m) furrows. Tomato seedlings were planted 5 days after treatment. An additional midseason application of 15 lb/acre (17 kg/ha)was applied to half of the 50 lb/acre (56 kg/ha) treatments and the total yields were compiled at the end of the harvest. In these trials, *single 50 lb/acre (56 kg/ha) preplant ozone treated plots saw increased total fruit production of approximately 57% compared to untreated controls. Those plots that also had a 15 lb/acre (17 kg/ha) midseason dosage had total marketable yield increases of 46% compared to yields in untreated control plots (see Figure 3-3).* The increased production with the absence of any soil-borne pathogen pressures again indicates a biostimulative component of soil ozonation.

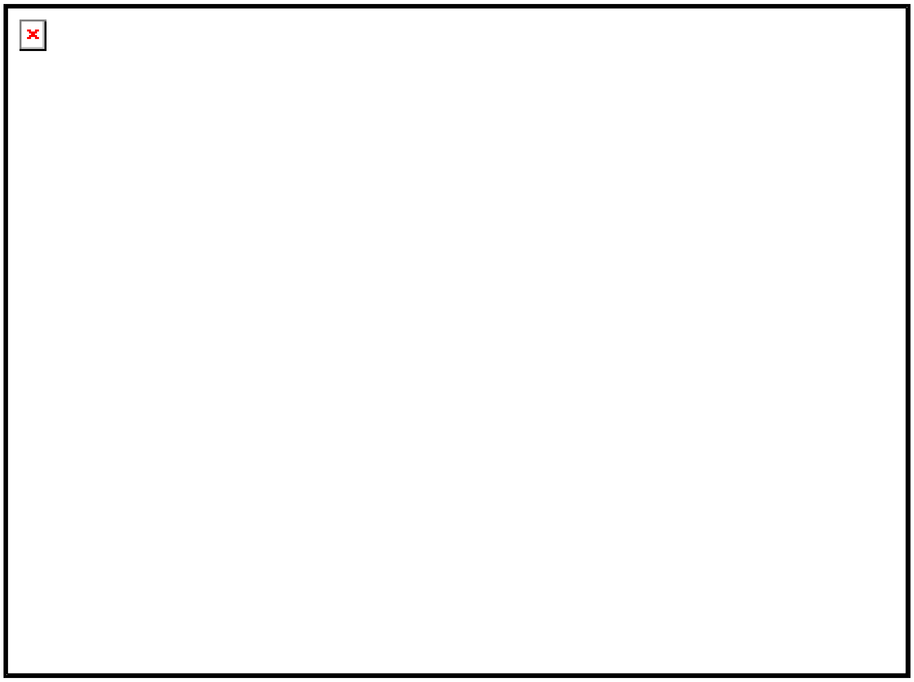

Figure 3-3
Tomato – Marketable Lbs/Plot

Carrots

- **1998 South Coast Carrot Field Trials** – These trials were performed in a manner similar to the tomato trials described above except that carrots were sown from seeds. Upon harvest, *plots treated with either 50 or 250 lbs/acre (56 or 280 kg/ha) of ozone following pre-irrigation showed a 92% increase in total marketable carrot yields compared to untreated controls and was only slightly less than Telone-emulsifiable concentrate and Vapam treated plots (see Figure 3-4).*

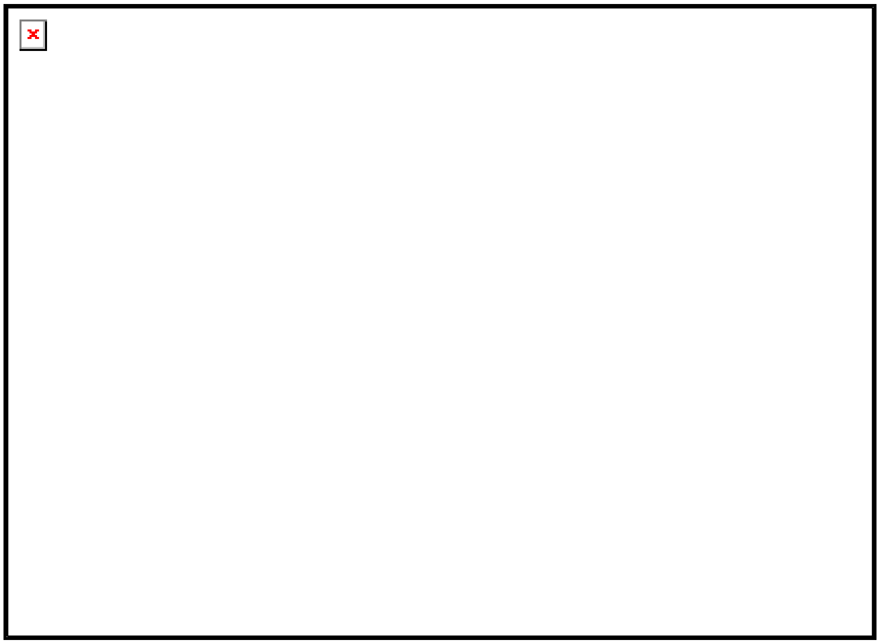

Figure 3-4
Carrots – Marketable Yield (Kg/Plot)

The total yield (including nematode damaged produce) was greatest in the 250 and 50 lb/acre (280 and 56 kg/ha) ozonated plots possibly indicating increased nutrient uptake in these plots (see Figure 3-5).

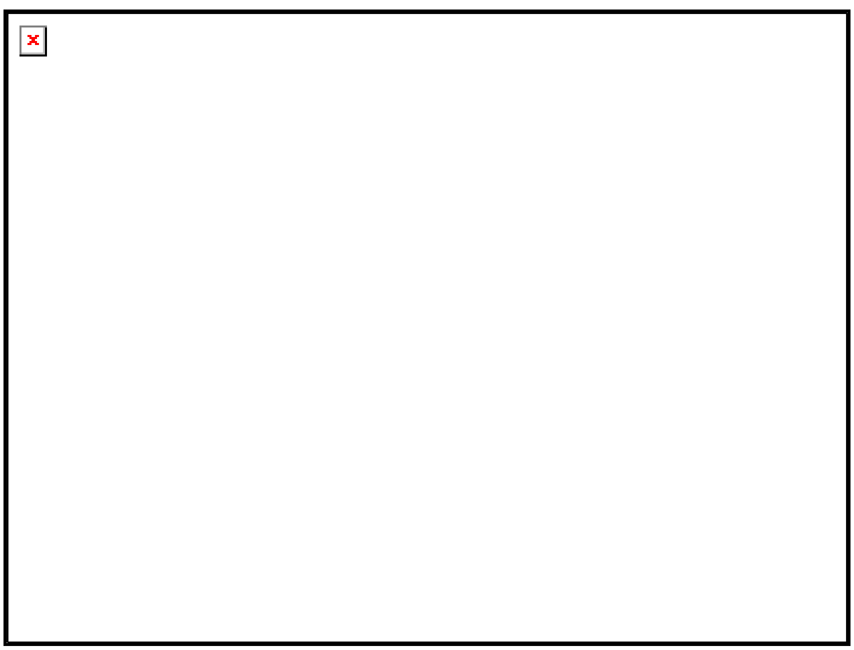

Figure 3-5
Carrots – Total Yield (Kg/Plot)

- **1998 AgTAC Carrot Field Trials** – These field experiments were performed during the summer through winter of 1998 at the Southern California Edison AgTAC Research Center in Tulare, California in conjunction with the Electric Power Research Institute – Agricultural Technology Alliance. Fields were free of known pathogens. Ozone was injected at the rate of 250 lb or 50 lb per acre (280 or 56 kg/ha) (some coextensively with 100 lb per acre (112 kg/ha) CO_2) through underground drip lines buried about 6 inches (152 mm) in the center of 48” (1.2 m) furrows. Carrot seeds were planted 5 days after treatment. Two additional midseason applications of 15 lb/acre (17 kg/ha) were applied to half of the 50 lb/acre (56 kg/ha) treatments. Upon harvest, carrots were segregated into marketable and non-marketable categories and weighed. When only the comparably seeded and irrigated plots are compared, *plots pretreated with 50 lbs/acre (56 kg/ha) of ozone and 100 lb per acre (112 kg/ha)* $C0_2$ *showed a 26% increase in total marketable carrot yields compared to untreated controls. Plots pretreated with 50 lbs/acre (56 kg/ha) of ozone and 2 midseason applications of 15 lb per acre (17 kg/ha) showed a 15% increase in total marketable carrot yields compared to untreated controls (see Figure 3-6).*

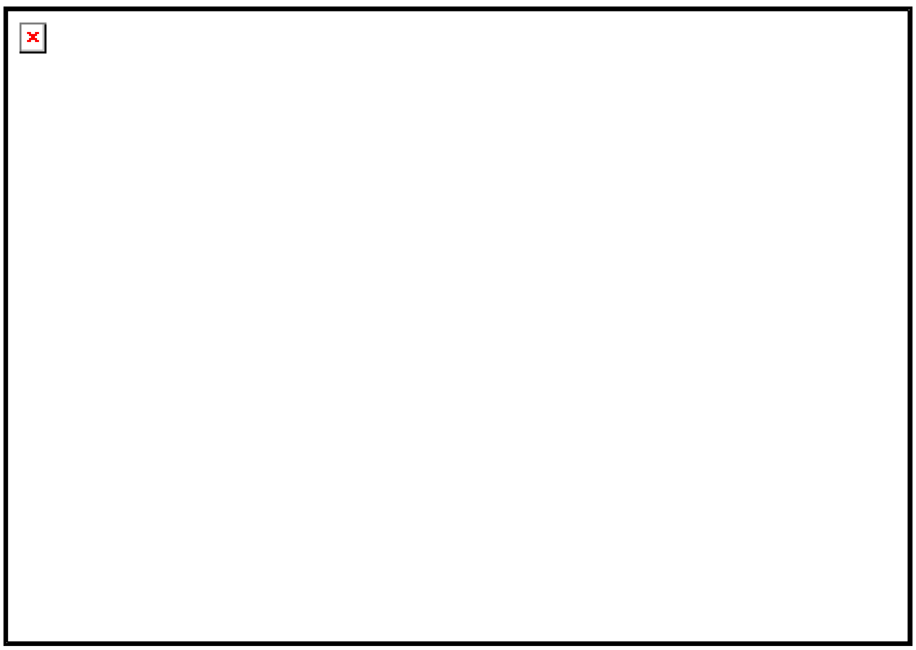

Figure 3-6
Carrots – Marketable Yield (Lb/Plot)

Strawberries

- **1997-98 Watsonville Strawberry Field Trials** – This experiment was performed at a site maintained by the USDA and the California Strawberry Commission in Watsonville California in conjunction with Dr. John Duniway of the UC Davis Department of Plant Pathology. At this site, the soil was heavily infested with *Verticillium* sp. fungi. Ozone was injected at the rate of 400 lb per acre (448 kg/ha) through drip tubing buried about 6” (152 mm) in the center of 36” (914 mm) beds. Ozonation applications were made with and without pre-inoculation with *Trichoderma* fungi followed by strawberry transplant planting

5 days later in November of 1997. Native populations of *Trichoderma* fungi have been shown to be stimulated by ozone. *Trichoderma* fungi have also been shown to be beneficial to many crops and the effect of ozone on commercial cultures and subsequent plant growth were thus explored. In early June 1998 an additional midseason application of 15 lb/acre (17 kg/ha) was made to those plots that had been previously inoculated with the *Trichoderma sp.* fungi. Cumulative yields totaled through the end of the growing season in early August showed *the ozonated plots with Trichoderma fungi produced 100% greater marketable fruit than untreated controls* and was *functionally equivalent to the methyl bromide/chloropicrin treated plots.* The plots that received ozone only were 54% greater than the untreated controls (see Figure 3-7).

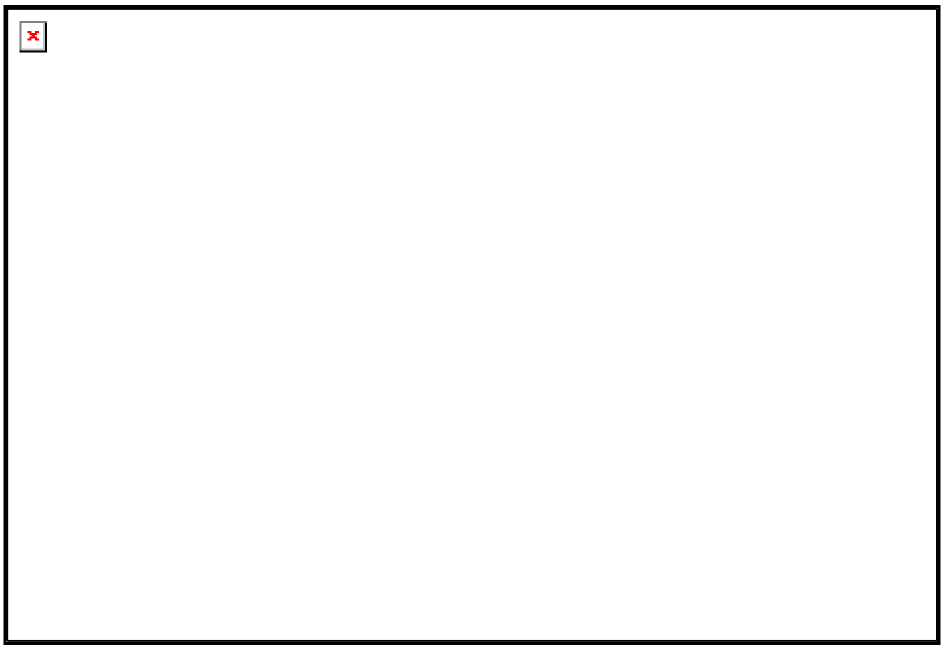

Figure 3-7
Strawberry – Marketable Yield (Gm/Plant)

Sugar Beets

- **1998 South Coast Sugar Beet Field Trials in Cyst Nematode Infested Soils** – These trials were performed in a field heavily infested cyst nematode (*Hetrodera schachtii* at the University of California South Coast Field Station in Irvine, California. The research was conducted in conjunction with Dr. Becky Westerdahl of the University of California at Davis Department of Nematology. Ozone was injected in early July with and without pre- and post-irrigation at the rate of 250 lb per acre (280 kg/ha) through underground drip tubing buried 4-6 inches (102-152 mm) in the center of 32” (813 mm) furrows. Each treatment consisted of six 20-ft. (6 m) rows in randomized complete blocks. Sugar beets (variety HH103) were planted 1 week later and the total yield was compiled at the end of the late December harvest.

In these trials, *no statistical differences in treatments were observed (see Figure 3-8).*

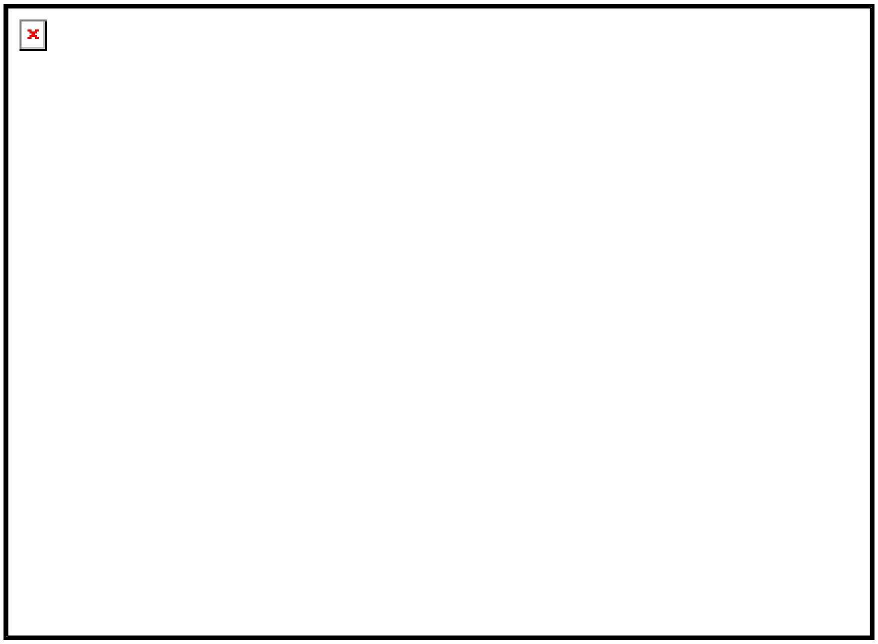

Figure 3-8
Sugar Beet – Cyst Nematode – Tons/Acre Equivalent

- **1998 South Coast Sugar Beet Field Trials in Root Knot Nematode Infested Soils** –These field experiments were also performed at the UC South Coast Field Station with Dr. Becky Westerdahl coextensive with the trials described above except that plots were in soils highly infested with the root knot nematode (*Meloidogyne javanica*). The methods and dates of applications were identical to those described above.

In these trials, preplant treatment with *50 lb* O_3*/acre (56 kg/ha) with 100 lb* CO_2*/acre (112 kg/ha) saw increased total production of approximately 3% compared to untreated controls and 7.5% compared to metam sodium treated plots and decreased yield of 18% compared to Telone treated plots (see Figure 3-9).* Further investigations are needed to explain cause and effect relationships.

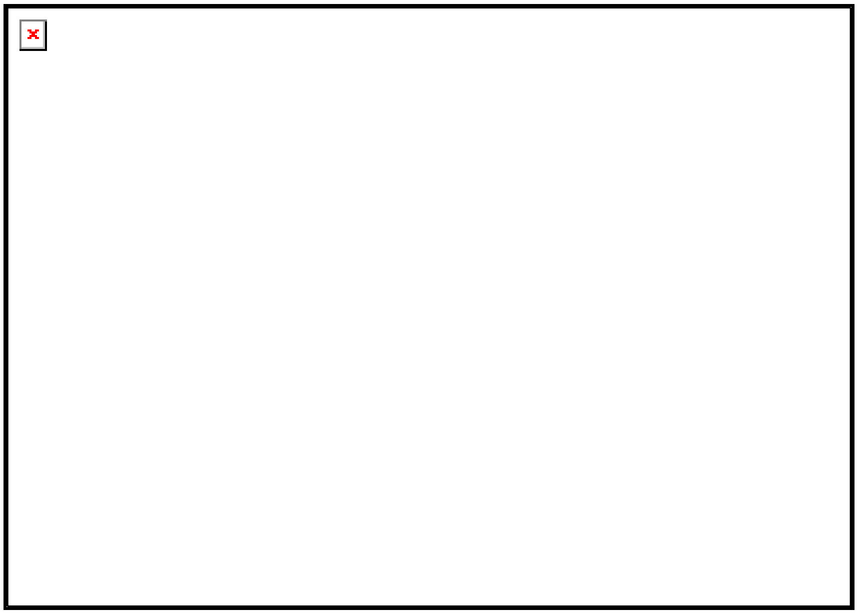

Figure 3-9
Sugar Beet – Root Knot Nematode – Tons/Acre Equivalent

Broccoli

- **1998 Broccoli Field Trials** – These experiments were performed in the summer of 1998 at a private farm in Santa Maria, California. Following ozone injection at 50 lb or 250 lb per acre (56 or 280 kg/ha) through drip lines buried 8” (203 mm) deep, broccoli seedlings were planted 5 days later. Upon harvest 10 weeks later, broccoli heads were segregated into export or domestic quality. Export heads are highly desirable because they have a 200 - 300% price premium over domestic quality heads. *The 50 lb per acre (56 kg/ha) ozone treated plots produced a 20% increase in number of export quality heads compared to the untreated controls (see Figure 3-10).*

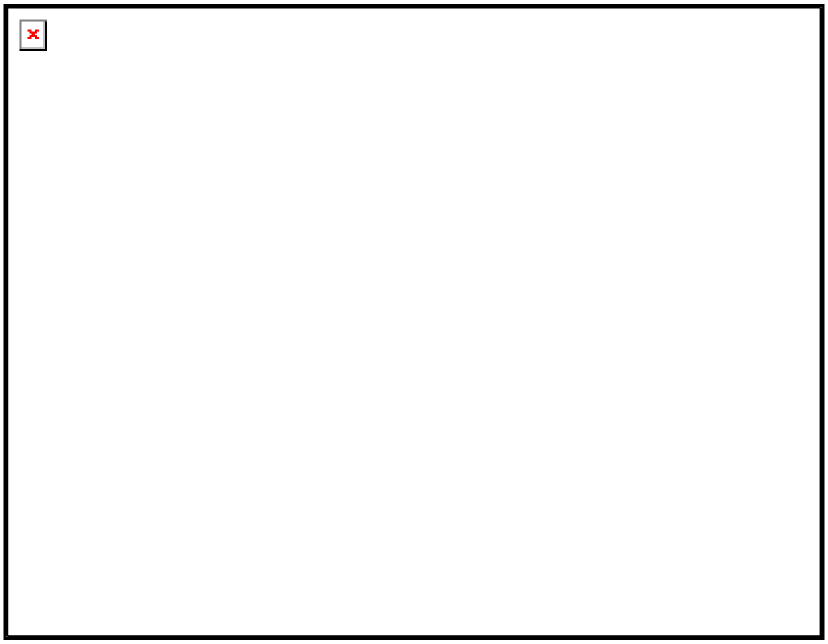

Figure 3-10
Broccoli Yield – Export Heads/Plot

Prunes

- **1997-98 Prune Orchard Replant Field Trials** – These trials were conducted in an established 30 year old prune orchard with severe lesion and ring nematode population pressures. Tree replant sites were backhoed in the fall to remove the stump and larger roots and remounded. Ozone was applied at the rate of 1.25 lbs (0.6 kg) per hole through an injection probe with 3/8” (10 mm) emitter holes drilled between 8 and 18” (203 and 457 mm) depth. Trees were planted 1 week later in March in the normal manner. The survival rate, tree diameter, and vigor were evaluated in November. *Trees planted in ozone treated holes had a 70% survival rate which was similar to the survival rates for trees grown in Enzone, Telone, and methyl bromide treated soils (see Figure 3-11).*

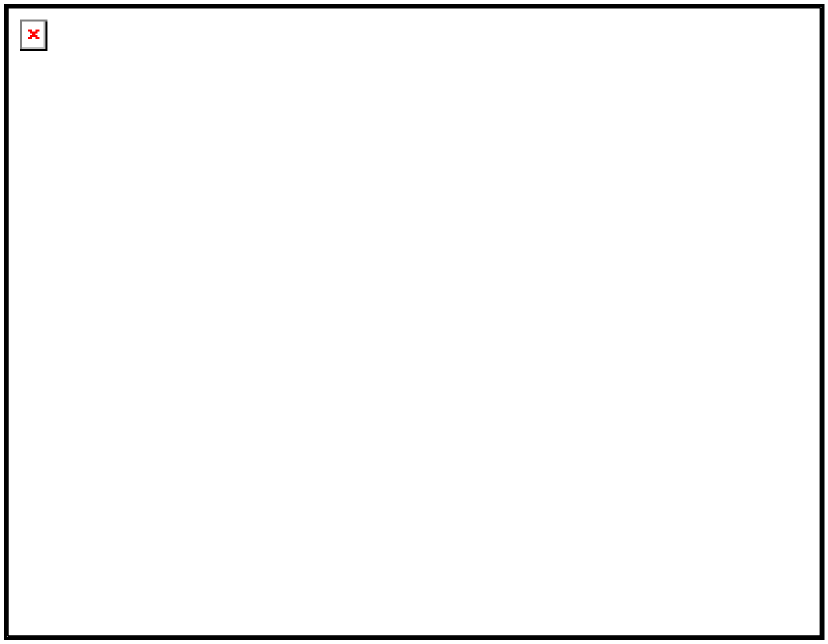

Figure 3-11
Prune Replants – Survival (%)

By multiplying the average vigor rating of the surviving trees by the survival percentage, an overall rating of treatment effectiveness is obtained. When so evaluated, *trees planted in ozone treated soil showed an overall rating greater than trees planted in untreated soils or soils treated with methyl bromide, Enzone, or Telone. Metam sodium treated trees exceeded the ozone treatment trees' overall rating only slightly (see Figure 3-12).*

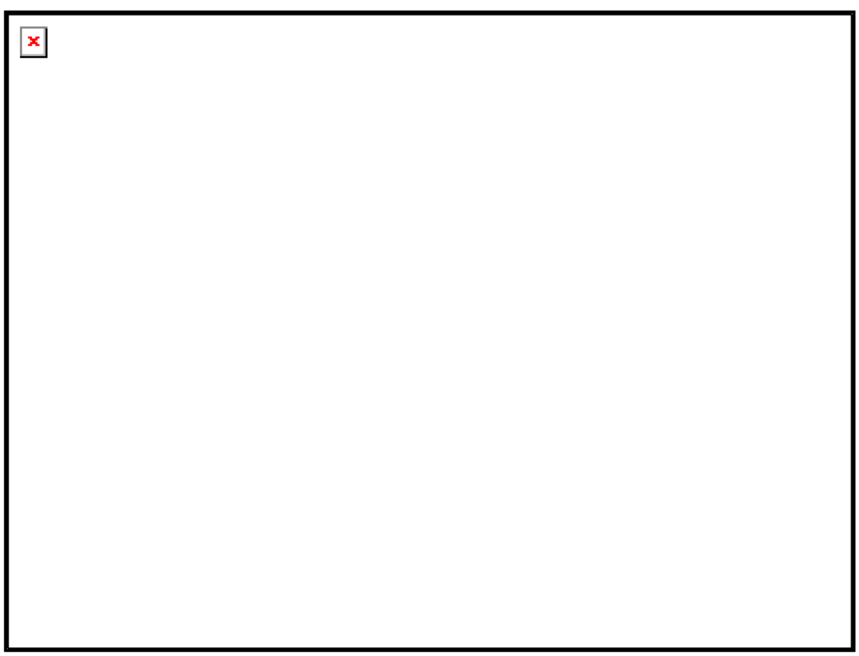

Figure 3-12
Prune Replants – Overall Rating = Survival % x Survivor Rating

Sweet Potatoes

- **1998 Sweet Potato Field Trials** – These experiments were performed in May through October of 1998 at a private farm in Stevenson, California. Following ozone injection in early May at 100 lb or 400 lb per acre (112 or 448 kg/ha) through drip lines buried 7" (178 mm) deep, sweet potato seedlings were planted 5 days later. Upon harvest in early October, potatoes were segregated into large marketable or small potatoes. *The 100 lb per acre (112 kg/ha) ozone treated plots produced an average 15% increase in large potato weights compared to the untreated controls (see Figure 3-13).* No statistical difference was measured between these three treatments.

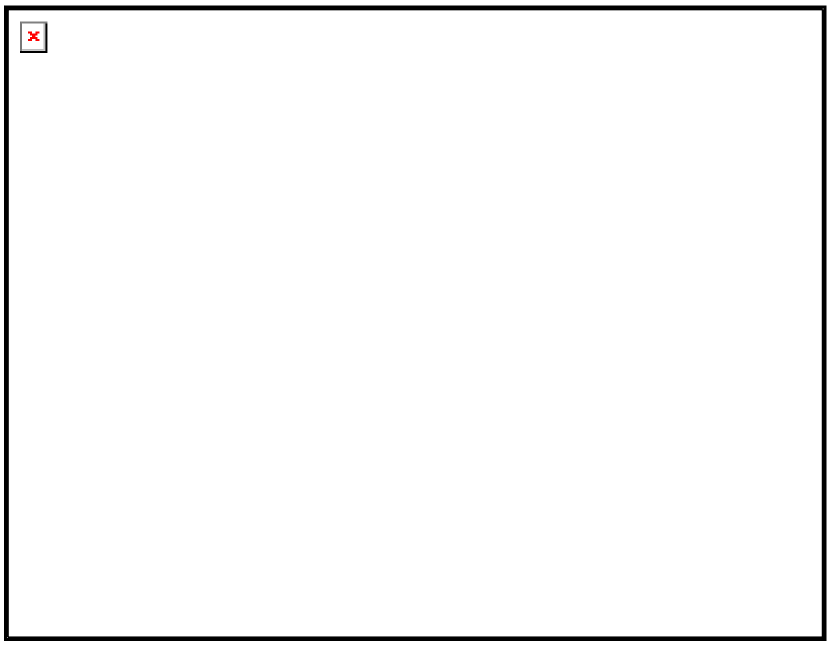

Figure 3-13
Sweet Potato Yield – Lbs Large Potatoes/Plot

Peaches

- **1998 Peach Tree Replant Trials** – These trials were conducted on the non productive periphery of an established 25 year old peach orchard. In the same manner as the prune trials, 1.25 lbs (0.6 kg) of ozone was injected into a backhoed and remounded tree site 5 days before trees were planted. The injection probe had eight 3/8" (10 mm) holes spaced around the probe at a buried depth of from 6-18" (152-457 mm) through which the ozone was injected into the probe. Within several weeks, an apparent phytotoxic effect was noticed in the trees that had been planted in ozonated soil (see Figure 3-14). The trunks of these trees turned a darker brown and the few leaflets that had formed were very small and very dark green. These are symptoms characteristic of nitrogen burn due to nitrogen in the soil. Subsequent soil analysis revealed nitrate nitrogen increased in the ozonated tree holes from 26 ppm to 149 ppm and ammonia nitrogen increased from 2.1 ppm to as high as 16 ppm (see Figures 3-15 and 3-16). It was concluded the phytotoxicity was probably caused by an excess formation of nitrogenous compounds in the soil resulting from over ozonation. These tests will be repeated with lower ozone dosages. A compounding factor in these trials was that many of the untreated control replants also showed poor vigor. It is believed that this was due to root fungus on the replant roots originating from improper handling after removal of the trees from cold storage. It is not known if similar results would have occurred if all the ozonated tree replants were not similarly afflicted.

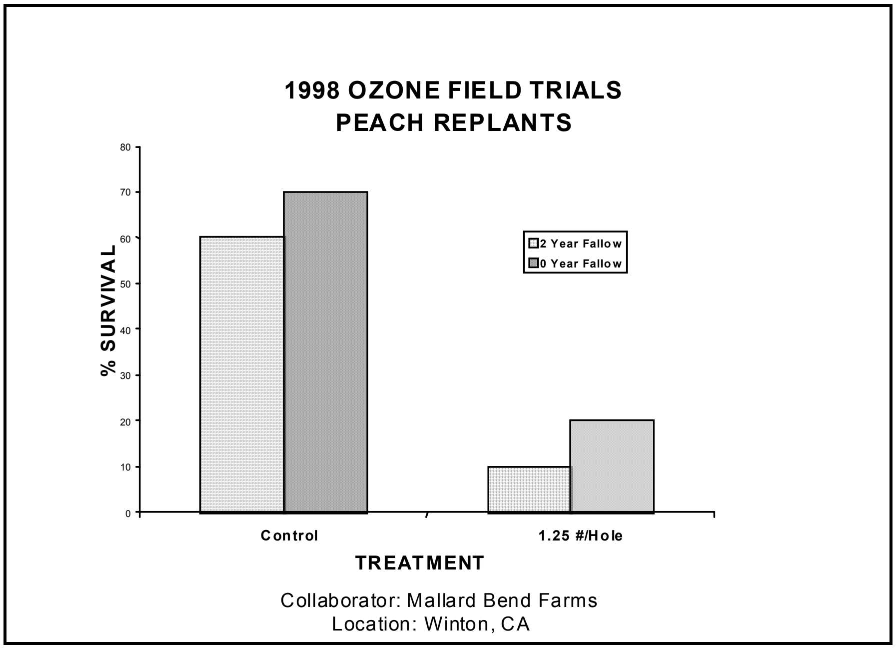

Figure 3-14
Peach Replants - % Survival

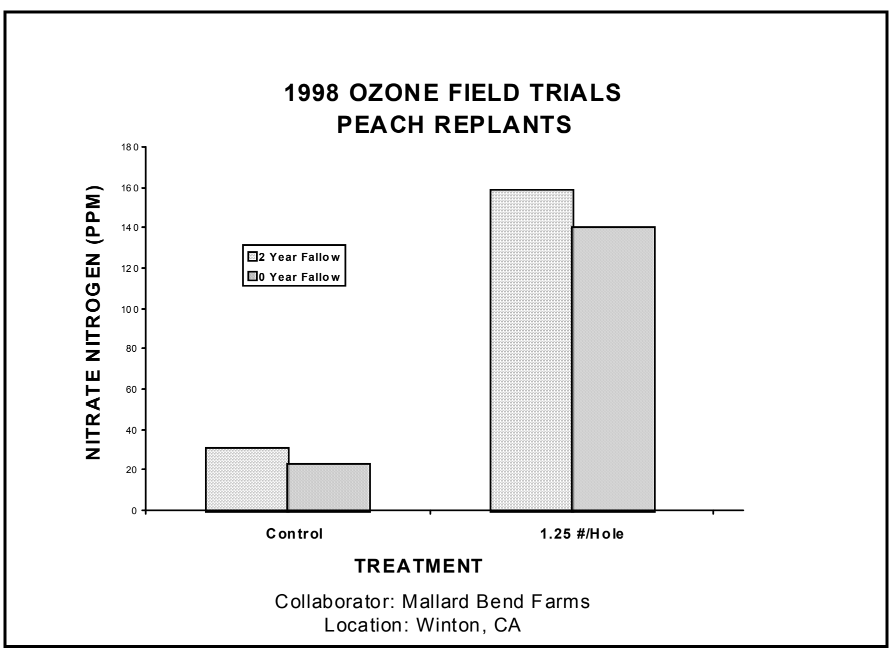

Figure 3-15
Peach Replants – Nitrate Nitrogen (PPM)

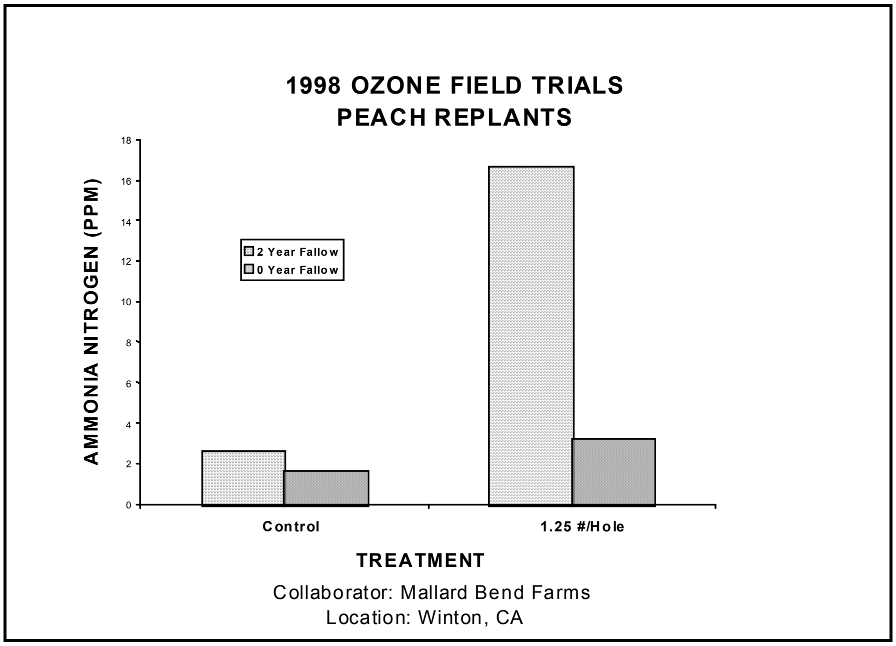

Figure 3-16
Peach Replants – Ammonia Nitrogen (PPM)

Interpretation of Results

The results of these field trials generally demonstrate the broad effectiveness of ozone treatment of soil in increasing plant yield and reducing the detrimental effects of soil pathogens in a variety of commercially important crops and soil. The results suggest that soil treatment with ozone results in somewhat decreased soil pathogen pressures (due to its biocidal effects) and increased nutrient availability (due to its oxidative effects on soil organics). Together, as a preplant treatment, these benefits promote increased plant growth and yield. Much additional work is necessary to be able to accurately predict the specific growth response achieved by ozonation in different crops grown in different soil types with different pathogens and different climatic conditions.

Modest levels of phytotoxicity were noted in the form of lower leaf burn in a number of plants in several plots upon midseason applications of only 15 or 25 lbs/acre (17 or 28 kg/ha) in the tomato and carrot trials in Tulare. The application of ozone in midseason in tomatoes at AgTAC resulted in a slightly lower yield than those plots not receiving ozonation. In contrast, the plots which received midseason ozonation applications in the strawberry trials in Watsonville, California showed substantially increased growth compared to plots which received only a pre-plant treatment. Further work needs to be performed to properly defined the correct dosage levels that yield the maximum growth response without phytotoxicity.

The effects of mixing carbon dioxide with the ozone gas when injected as pre-plant treatment were mixed. In the case of the tomato and sugar beet trials in root knot nematode laden soil in Irvine and carrot trials in Tulare, coextensive use of carbon dioxide resulted in increased yield. The opposite effect was seen in the carrot trials in root knot nematode laden soil and sugar beet trials in cyst nematode laden soils in Irvine. Further field trials are necessary to properly predict the effects of such treatments in future applications.

Some numerical increases in total fungal biomass were noted in some trials but not in others. The differences were not statistically significant at the 90% confidence level The underlying mechanisms of such stimulation are not known and further laboratory work is required in conjunction with field experiments in order to further our understanding.